HETEROGENEOUS NETWORKING FOR BEYOND 3G SYSTEM IN A HIGH-SPEED TRAIN ENVIRONMENT

Investigation of handover procedures in a high-speed train environment and adoption of a pattern classification neural-networks approach for handover management

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ABSTRACT

Name:	Felicia Li Chin Ong
Thesis Title:	Heterogeneous Networking for Beyond 3G system in a High-Speed Train Environment
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Based on the targets outlined by the EU Horizon 2020 (H2020) framework, it is expected that heterogeneous networking will play a crucial role in delivering seamless end-to-end ubiquitous Internet access for users. In due course, the current GSM-Railway (GSM-R) will be deemed unsustainable, as the demand for packet-oriented services continues to increase. Therefore, the opportunity to identify a plausible replacement system conducted in this research study is timely and appropriate.

In this research study, a hybrid satellite and terrestrial network for enabling ubiquitous Internet access in a high-speed train environment is investigated. The study focuses on the mobility management aspect of the system, primarily related to the handover management. A proposed handover strategy, employing the RACE II MONET and ITU-T Q.65 design methodology, will be addressed. This includes identifying the functional model (FM) which is then mapped to the functional architecture (FUA), based on the Q.1711 IMT-2000 FM. In addition, the signalling protocols, information flows and message format based on the adopted design methodology will also be specified. The approach is then simulated in OPNET and the findings are then presented and discussed.

The opportunity of exploring the prospect of employing neural networks (NN) for handover is also undertaken. This study focuses specifically on the use of pattern classification neural networks to aid in the handover process, which is then simulated in MATLAB. The simulation outcomes demonstrated the effectiveness and appropriateness of the NN algorithm and the competence of the algorithm in facilitating the handover process.

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LIST OF ACRONYMS

2G	Second-Generation
2.5 G	Generation 2.5
3G	Third-Generation
4G	Fourth-Generation
5G	Fifth-Generation
3GPP	Third Generation Partnership Project
3GPP2	Third Generation Partnership Project 2
16QAM	16 Quadrature Amplitude Modulation
ACK	Acknowledgement
ADC	Analogue-to-Digital Converter
AI	Artificial Intelligence
ALG	Application Layer Gateway
AMPS	Advanced Mobile Phone System
ANN	Artificial Neural Network
AP	Access Point
ART	Adaptive Resonance Theory
ASEL	Antenna Selection
ATM	Asynchronous Transfer Mode
AuC	Authentication Centre
BB	Baseband
BC	Bearer Control
BER	Bit Error Rate
BIA	Bump in the API
BIS	Bump in the Stack
BLA	BP Learning Algorithm
BM-SC	Broadcast Multicast-Service Centre
BP	Backpropagation
BPSK	Binary Phase Shift Keying
BSA	Basic Service Area
BSC	Base Station Controller
BSM	Broadband Satellite Multimedia
BSS	Basic Service Set

BTS	Base Transceiver Station
BW	Bandwidth
CAGR	Compound Annual Growth Rate
CCA	Clear Channel Assessment
CCK	Complementary Code Keying
CDN	Content Delivery Network
CF	Compact Flash
CIC	Confidentiality and Integrity Control
CIP	Cellular IP
CN	Core Network
CNR	Carrier-to-Noise Ratio
CS	Circuit- Switched
CS-MGW	Circuit Switched-Media Gateway
CSMA	Carrier Sense Multiple Access
DAD	Duplicate Address Detection
DBPSK	Differential BPSK
DCH	Dedicated Channel
DDB	Database
DECT	Digital Enhanced Cordless Telecommunications
DLR	Delta Learning Rule
DNS	Domain Name System
DPDCH	Dedicated Physical Data Channel
DQPSK	Differential QPSK
DS	Distribution System
DSRC	Dedicated Short Range Communications
DSSS	Direct Sequence Spread Spectrum
DSTM	Dual Stack Transition Mechanism
DVB	Digital Video Broadcasting
DVB-RCS	DVB-Return Channel Satellite
DVB-S	DVB-Satellite
DVB-S2	DVB-S Second Generation
DVB-T	DVB-Terrestrial
EDGE	Enhanced Data Rates for Global Evolution

EIR	Equipment Identity Register
EIRENE	European Integrated Railway Radio Enhanced Network
EPC	Evolved Packet Core
ER	Edge Router
ERA	European Railway Agency
ESS	Extended Service Set
ETSI	European Telecommunications Standard Institute
EU	European Union
EUL	Enhanced Uplink
F	Activation Function
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
FE	Functional Entity
FEA	FE Action
FES	Fixed Earth Station
FHSS	Frequency Hopping Spread Spectrum
FI	Functional Interface
FIFO	First-In-First-Out
FIFTH	Fast Internet for Fast Train Hosts
FM	Functional Model
FSS	Fixed Satellite Service
FUA	Functional Architecture
GEO	Geostationary Earth Orbit
GGSN	Gateway GPRS Support Node
GMSC	Gateway Mobile Switching Centre
GMSC-S	GMSC Server
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GSM-R	GSM-Railway
GTW	Gateway
H	Hessian Matrix
H2020	Horizon 2020
HC	Handover Criteria

HCA	HC Adjustment
HD	Handover Decision
HE	Handover Execution
HI	Handover Initiation
HLR	Home Location Register
HMPM	Handover Mobile Terminal Profile - MT
HMPN	Handover Mobile Terminal Profile – Network (HMPN)
HN	Home Network
HO	Handover
HOC	Handover Execution Control
HSCSD	High-Speed Circuit-Switched Data
HTTP	Hypertext Transfer Protocol
ICMP	Internet Control Message Protocol
IEEE	Institute of Electrical and Electronic Engineers
IETF	Internet Engineering Task Force
IN	Intelligent Network
INF	Information Flow
IMR	Intermediate Module Repeater
IMS	IP-Multimedia Subsystem
IMT-2000	International Mobile Telecommunications-2000
IF	Intermediate Frequency
I/O	Input/Output
IP	Internet Protocol
IPv4	IP version 4
IPv6	IP version 6
IR	Infrared
ISATAP	Intrasite Automatic Tunnel Addressing Protocol
ISDN	Integrated Services Digital Network
ISHO	Inter-Segment Handover
ISL	Inter-Satellite Links
ISM	Industrial Scientific and Medical
IST	Information Society Technologies
ITS	Intelligent Transportation Services
ITU	International Telecommunications Union

J	Jacobian Matrix
LDF	Location Detection Function
LDPC	Low-Density Parity Check
LEO	Low Earth Orbit
LLC	Logical Link Control
LTE	Long Term Evolution
LUH	Location Update Handler
LVM	Levenberg-Marquardt
MA	Mobility Agent
MAC	Medium Access Control
MAHO	Mobile Assisted Handover
MEF	Measurement Function
MCHO	Mobile Controlled Handover
MGPF	Mobile Geographic Position Function
MIB	Management Information Database
MIP	Mobile IP
MIPv4	MIP version 4
MIPv6	MIP version 6
MLP	Multi-Layered Perceptron
MMI	Modem Management Interface
MMT	Multi-Mode Terminal
MN	Mobile Node
MOWGLY	Mobile Wideband Global Link System
MPDU	MAC Protocol Data Unit
MPE	Multi-Protocol Encapsulation
MPEG	Moving Pictures Experts Group
MPLS	Multiprotocol Label Switching
MS	Mobile Station
MSC	Mobile Switching Centre
MSC-S	MSC Server
mse	Mean Squared Error
MSS	Mobile Satellite Service
MT	Mobile Terminal
NA	Network Architecture

NAHO	Network Assisted Handover
NAK	Negative Acknowledgement
NaN	Not-a-Number
NAPT-PT	Network Address Port Translation+Packet Translation
NATO	North Atlantic Treaty Organisation
NAT-PT	Network Address Translation-Protocol Translation
NBMA	Non-Broadcast Multiple Access
NCC	Network Control Centre
NCHO	Network Controlled Handover
N-IWU	Network Inter-working Unit
NE	Network Entity
NN	Neural Networks
OFDM	Orthogonal Frequency Division Multiplexing
OSPF	Open Shortest Path First
PC	Personal Computers
PCI	Peripheral Component Interconnect
PCMCIA	Personal Computer Memory Card International Association
PCNN	Pattern Classification NN
PCU	Packet Control Unit
PDA	Personal Digital Assistant
PE	Physical Entity
PHY	Physical Layer
PI	Physical Interface
PLCP	Physical Layer Convergence Protocol
PLMN	Public Land Mobile Network
PLR	Perceptron Learning Rule
POA	Point of Attachment
PS	Packet-Switched
PSMP	Power Save Multipoll
PSTN	Public Switched Telephone Network
QIF	Quality Information Function
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying

RAN	Radio Access Network
RBF	Radial Basis Function
RD	Reverse Direction
RF	Radio Frequency
RIP	Routing Information Protocol
RNC	Radio Network Controller
RNS	Radio Network Subsystem
ROC	Receiver Operating Characteristic
RSS	Received Signal Strength
RSS_{sat}	RSS of the Satellite Access Segment
RSSI	RSS Indicator
RSS_{thres}	RSS Threshold
RSS_{wlan}	RSS of the W-LAN Access Segment
Rx	Receiver
SAE	System Architecture Evolution
SAT_ACC	Satellite Access Network
SAT-MT	Satellite Mobile Terminal
SatNEx	Satellite Communication Network of Excellence
SAT-SEG	Satellite Segment Output
SBC	Switching and Bridging Control
SGSN	Serving GPRS Support
SHRM	Special Handover Request - MT
SIIT	Stateless IP/Internet Control Message Protocol Translation
SLFN	Single Hidden Layer Feedforward Network
S-MBMS	Satellite Multimedia Broadcast Multicast Service
SMTP	Simple Mail Transfer Protocol
SOM	Self-Organising Map
STBC	Space-Time Block Coding
S-UMTS	Satellite-UMTS
TCCM	Target Cells and Connection - MT
TCCN	Target Cell and Connection - Network
TCP	Transmission Control Protocol
TE	Terminal Equipment

T-IWU	Terminal Inter-working Unit
TRT	Transport Relay Translator
T-UMTS	Terrestrial-UMTS
Tx	Transmitter
UDP	User Datagram Protocol
UE	User Equipment
UFM	Unified Functional Model
UIC	International Union of Railways
UIMF	User Identification Management Function
ULE	Ultra Light Encapsulation
UMTS	Universal Mobile Telecommunications System
USB	Universal Serial Bus
USRAN	UMTS Satellite RAN
UTRAN	UMTS Terrestrial RAN
VE	Vehicular Environment
VHO	Vertical Handover
VLR	Visitor Location Register
VPN	Virtual Private Network
WAVE	Wireless Access in a Vehicular Environment
WEP	Wired Equivalent Privacy
WG	Workgroup
WiFi	Wireless Fidelity
W-LAN	Wireless LAN
WLAN-MT	W-LAN Mobile Terminal
WLAN-SEG	W-LAN Segment Output
XOR	Exclusive OR

1 INTRODUCTION

1.1 Research Motivation

In [1], it states that the global mobile data traffic has grown by 70% from 2012 to 2013. In addition, it was predicted that the demand for mobile networking will continue to grow at a compound annual growth rate (CAGR) of 66% from 2012 to 2017, which demonstrates the significant shift in paradigm towards packet-oriented services in mobile communications. Moreover, the increasing demand by consumers for mobile networking while commuting, sees an emerging trend in developing Internet infrastructure and applications for a vehicular environment (VE), as stated in [2].

In 2000, the development of the specifications for supporting data and voice services in a railway environment were finalised in 2000 and are now maintained by the International Union of Railways (UIC). The approach was based on the Second-Generation (2G) cellular system, Global System for Mobile Communications (GSM), and is specifically known as GSM-R. GSM-R has since then been globally deployed as the acknowledged platform for supporting mobile communications in a railway environment and has been deemed a reliable system for nearly a decade. It is foreseeable that GSM-R will gradually be an insufficient and out-dated system to support bandwidth demanding applications and services, as technologies progress. Further research developments, such shown in [3], focuses mainly on providing wireless Internet access to high-speed trains employing WiFi and Worldwide Interoperability for Microwave Access (WiMAX) technologies.

This architecture takes into consideration the IEEE 802.21 standard [4] that defines mechanisms for optimising handover (HO) between different IEEE 802 and cellular systems. Besides a WiFi/WiMAX architecture, the adoption of cellular systems, mainly Long Term Evolution (LTE), for supporting Internet access for high-speed trains has also been addressed in [5]. The architecture looks at supporting 2G, 3G and WiFi services within the train carriages to end users and communication from the train to the network service provider will be via LTE. The potential of adopting LTE as a replacement for GSM-R in rail communication for traffic management is also specified in [6], which explores the potential of LTE as a successor to GSM-R for critical communications.

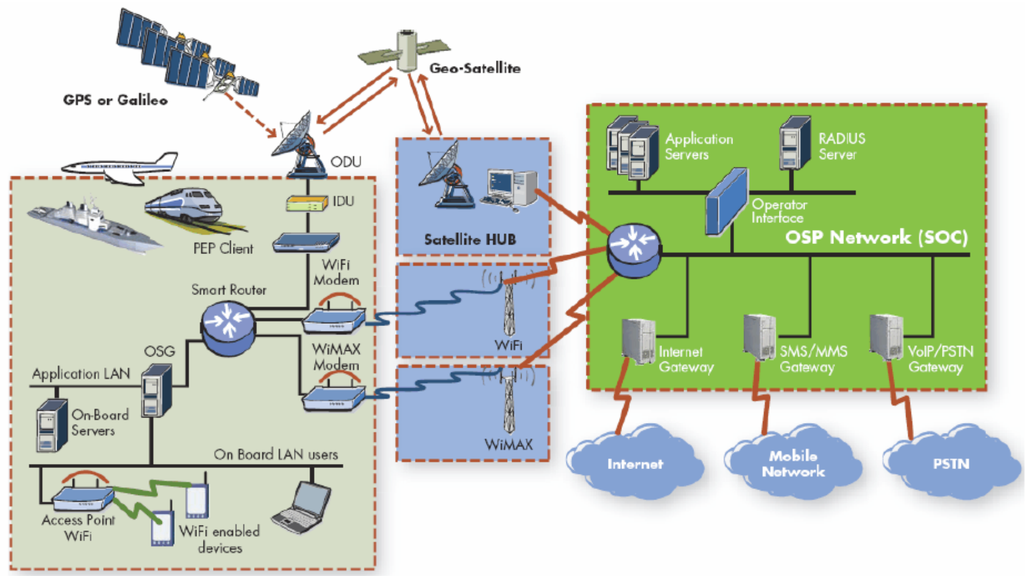

Figure 1-1: Reference Architecture based on the MOWGLY system [7]

Another architecture, see Figure 1-1, addressed in [7] adopts the MOWGLY (Mobile Wideband Global Link System) architecture, for providing broadband internet access for aircraft, trains and ships using satellite, WiFi and WiMAX systems [8]. Other cases studies employing different wireless technologies, such as GPRS, HSDPA, WiFi, WiMAX, satellite, radio-over-fibre, as potential network infrastructures for providing broadband Internet access in a rail environment was discussed in [9]. In [9], it also mentioned the EU (European Union) sponsored Information Society Technologies (IST) project: Fast Internet for Fast Train Hosts (FIFTH). The project began in 2000 and investigated the feasibility of employing satellite and WiFi networks to provide heterogeneous network services and access to users on a high speed train. The architecture from the FIFTH project will be used as the basis for the work that is performed in this research, which spanned from 2002 to 2010 and was then continued from 2013.

The architecture in this research has similarities to the approach that is adopted in MOWGLY, but the FIFTH architecture focuses on employing a single access network model using wireless technologies to extend the satellite coverage to trains. Therefore, from the perspective of the network, handover is only required to be performed in the lower layers, as there is no change in the point-of-attachment in the network layer. In essence, as future technology progresses and consumer demand trend changes, there will always be a demand for viable solutions to address challenges and issues for supporting Internet access in a high-speed train environment.

Another aspect of the research looks at incorporating geographical location information to aid the handover process in high-speed trains. The daily route of a train journey remains relatively similar most of the time and using the geographic location of the train will be favourable for handover. The concept of location-aided handover has been widely addressed over the years. Most recent research activities focus on a homogeneous network, with algorithms designed specifically for a particular wireless technology, such as those in [10-12]. In [5] and [13], location-aided handover schemes are proposed for high-speed railways but the schemes consider a homogeneous network, such as LTE and GSM. There have been published materials on location-aided handover in a heterogeneous network environment, mainly designing schemes for low-mobility mobile devices. For instance, references [14-16] present location-aided vertical handover (VHO) schemes for mobile users that are catered for in a WiFi/Cellular system architecture. The introduction of a location-aided handover scheme for WiMAX/WiFi integrated networks is presented in [17] and employing an optimised location-aided handover scheme for 2G/3G cellular systems is addressed in [18]. Therefore, designing a location-aided handover scheme employing satellite and wireless technologies that can be adopted for a high-speed train environment is a research area that is yet to be explored and is the baseline scenario that is embarked in this research.

The research also looks into adopting a pattern classification NN for the handover. Previous research on pattern classification for handover has been addressed in the following references [19-21], however, most approaches only take into consideration the received signal strength (RSS) for the handover decision. For instance, in [20], the algorithm focuses on the handover between two base stations in a cellular network. The algorithm is suitable for a homogeneous network, as it takes into consideration the RSS of the cell coverage within a cellular system and handover is based on determining the drop in RSS of the mobile station, known as the corner effect. In [21], pattern classification was used to determine when handover should be initiated for a microcellular system. The approach takes into consideration the signal strength measurements, such as Rayleigh fading, path loss and shadow fading, assuming that such characteristics remain the same when a user travels down the same route. The algorithm is suitable for homogeneous networks and is largely dependent on frequent RSS measurements reporting from surrounding base stations to be made available. This will put a strain on network resources, as constant signalling messages will consume the available bandwidth in systems that will be better used for other purposes. However, it can be seen from [19-21] that the practicality of applying pattern classification NN in handover is feasible. In this research study, a novel approach of adopting a location-aided handover algorithm employing pattern classification NN will be addressed. The approach will take into consideration the RSS and geographical location of the train to determine which access technology the train should handover to. The trained NN will then be evaluated to determine the performance of the trained NN algorithm.

1.2 Aims and Objectives

The research study aims to investigate the handover management procedures in a hybrid satellite and terrestrial network for high-speed trains. In addition, the research aims to specify a novel location-aided approach that can be employed in the handover decision algorithm for heterogeneous networking. Therefore, the objectives of the project can be determined as follows:

- Investigate the viability of employing a hybrid satellite and terrestrial network architecture for a high-speed train environment;
- Identify the requirements of the adopted system, by designing suitable mobility management protocols, mainly on handover, needed to support ubiquitous Internet access in a high-speed train environment;
- Explore the feasibility of employing a pattern classification neural network (PCNN) for a location-aided vertical handover in a heterogeneous high-speed train network.
- Implement the designed handover methodology in OPNET and simulate the adopted PCNN handover algorithm in MATLAB;
- Review and conclude the performance outcomes that were achieved in the OPNET and MATLAB simulation that is the end-to-end delay achieved in OPNET and accuracy performance of the handover algorithm that was gathered in MATLAB.

1.3 Research Contributions

The contributions of the research are listed as follow:

- The thesis proposes a hybrid satellite and terrestrial framework for supporting ubiquitous Internet access in a rail environment. The terrestrial aspect of the system employs WiFi, as a gap filler technology to extend the satellite signal. These two technologies are well-established systems that have been widely research and in this thesis, the integration of the two systems as a single access network is recommended. This approach alleviates the need for handover in the network layer, which will decrease the complexity of the handover procedure and reduce the signalling load during handover.

- Within this thesis, a proposed location-aided HO management scheme for a hybrid satellite/terrestrial system is proposed. Besides the parameters in a conventional HO algorithm, the scheme also takes into account the geographical location of the train to facilitate the vertical HO process. This requires functional models and architectures, signalling protocols and message formats to be specified and designed.
- A novel handover decision algorithm for location-aided vertical handover in a hybrid satellite/terrestrial system was proposed. The approach adapts the pattern classification neural network for the handover decision and three training algorithms, Levenberg-Marquardt (LVM), Scaled Conjugate Gradient BP (SCG), Resilient BP (RBP), were used in the training of the NN algorithm. This is to determine which algorithm is able to provide an accuracy performance that is similar to the benchmark that is specified in the GSM-R system. Due to the three training algorithms adopted, three different NN architecture are required, as each algorithm requires a different topology to successfully train, validate and test the NN.
- A simulation framework of the proposed mobility management scheme for the hybrid wireless system was developed in OPNET. The functional models that was specified in the design methodology were mapped onto the network architecture. This is then simulated

in OPNET, including the signalling protocols, information flows and message formats. The end-to-end delay performances of the simulation model due to handover was then compared, evaluated and validated against the numerical analysis that was calculated.

- A proposed simulation framework of the PCNN handover decision algorithm for the hybrid wireless system was implemented in MATLAB. The simulation model is a back propagation multi-layered perceptron (MLP), which consists of one input layer, one output layer and one hidden layer. The three NN architectures that was identified, consists of different number of hidden nodes respectively. The training algorithms, LVM, SCG and RBP, were all applied to each architecture and performance outcomes from two phases were determined. The first phase is the training, validation and testing phase that is trained with the first dataset and the results presented on a confusion plot. The second phase is when the three trained PCNN classifier was then evaluated using another dataset to determine the generalisation behaviour of the classifier. The outcomes were represented in the confusion plots and Receiver Operating Characteristic (ROC) plots. The accuracy performances that were achieved from the two phases were then analysed, compared and evaluated.

1.4 Report Outline

This thesis comprises of seven main chapters and are presented as follows:

- Chapter 1 addresses the research purpose and motivation of this research. This includes identifying the aims and objectives that will be achieved.
- Chapter 2 discussed about the different wireless technologies applicable to this research and includes a background of the mobile systems, satellite system and wireless LAN technology. Moreover, a significant shift in paradigm towards providing packet-switched services for 4G systems and beyond; highlights the importance of supporting Internet Protocol (IP) networking for future generation of mobile systems. Therefore, the developments of the Internet Phenomenon, including IP mobility, will also be addressed in this chapter.
- The mobility management procedures, mainly concentrating on handover, will be introduced in Chapter 3. This includes a background review of the handover processes and schemes for handover management.
- Based on the background review of the project, the *modus operandi* of the system is addressed in Chapter 4 and the depicted system and network architecture and the preferred design methodology applied will also be elaborated.
- Chapter 5 presents the handover decision algorithm, and the approach that was adopted in this research. The chapter will also provide a brief review of NN, the basic concepts behind NN and the backpropagation

NN algorithm. The Levenberg-Marquardt algorithm that will be applied in the training of the NN algorithm will also be described.

- The approaches that were identified in Chapters 4 and 5 are then implemented using simulation tools, OPNET and MATLAB, and are presented in Chapter 6. The results, performance and observations achieved in the simulation will also be outlined.
- The project is then summarised and concluded in Chapter 7. Further recommendations on future directions that this research project can embark on will also be elaborated.

2 REVIEW OF CURRENT STATE-OF-THE-ART

2.1 Scope

The aim of this chapter is to provide a fundamental overview of the concepts that will be relevant and applicable for the purpose of this research study. In Section 2.2, a brief overview of the established wireless networks, GSM and Institute of Electrical and Electronics Engineers (IEEE) 802.11 Wireless LAN (also known as WiFi, WLAN or W-LAN) is provided. A background case study of heterogeneous networking between a satellite and cellular system will be presented in Section 2.4. The IP protocol is a connectionless network layer protocol that is designed for addressing and forwarding of IP packets (also known as IP datagrams) and plays an important role in supporting an all-IP network for 4G systems and beyond. A general overview of the IP protocol, i.e. IP version 4 (IPv4) and IP version 6 (IPv6), and IPv4 to IPv6 migration strategies are discussed in Section 2.5.

2.2 Wireless Networks Overview

2.2.1 Mobile Networks

The success deployment of the European Telecommunications Standard Institute (ETSI) GSM system [22], which is regarded as a 2G mobile cellular system that supports digital radio transmission for traffic, has led to rapid developments in the mobile communication sector. The 2G GSM architecture and its system components are shown in Figure 2-1.

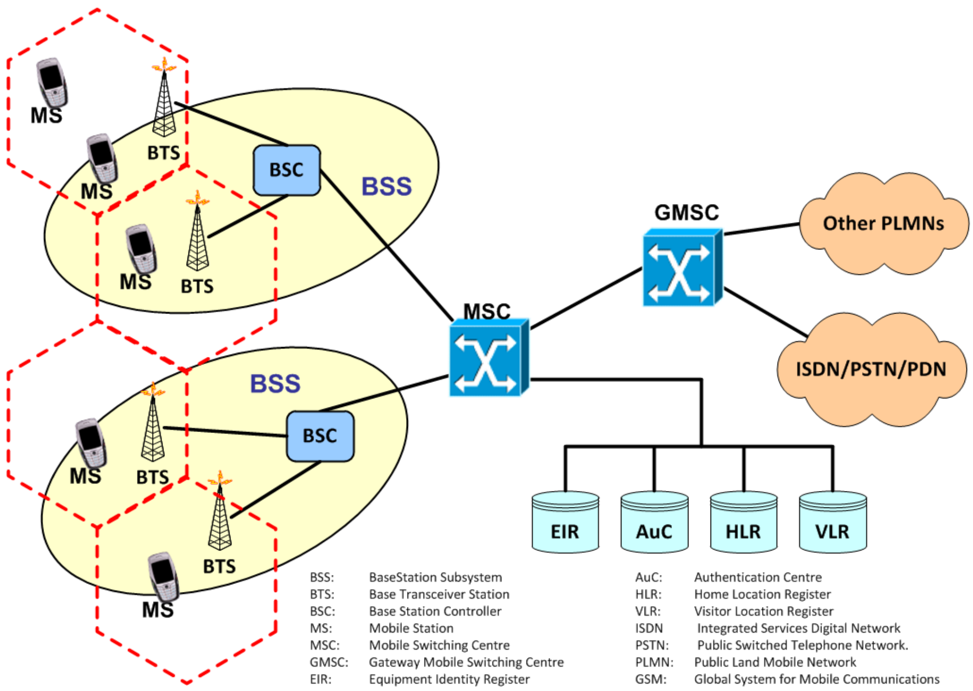

Figure 2-1: GSM System Architecture

Further enhancements to GSM were introduced and widely accepted as "Generation 2.5" (2.5G). The upgraded GSM system is capable of supporting either one or more of the following technologies: General Packet Radio Services (GPRS), High-Speed Circuit-Switched Data (HSCSD) or Enhanced Data Rates for Global Evolution (EDGE).

In Figure 2-2, it can be seen that GPRS reutilises the available underlying GSM infrastructure by overlaying a packet based air interface on to the existing circuit-switched GSM network. Several new components are introduced, such as Packet Control Unit (PCU), Serving GPRS Support Node (SGSN) and Gateway GPRS Support Node (GGSN). This enables mobile networks to provide consumers with both packet-switched (PS) and circuit-switched (CS) data services. The upgrade to support GPRS in GSM networks is deemed necessary, because the 3G core network, as defined by the Third Generation Partnership Project (3GPP), is based on the joint

GSM and GPRS core network. Further information on GSM and GPRS systems are available in [22-25].

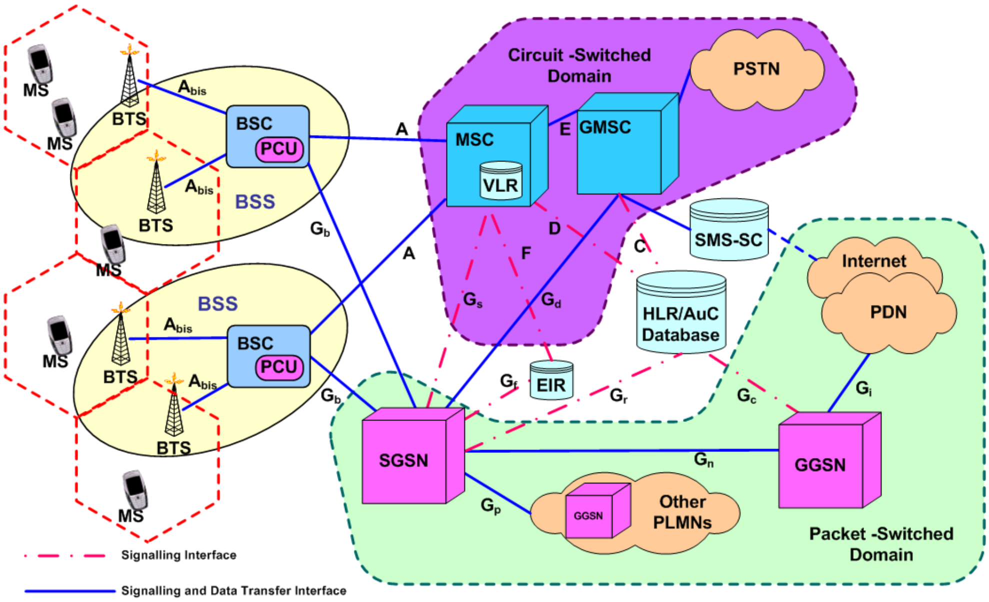

Figure 2-2: GPRS System Architecture

In 1992, the International Union of Railways (UIC) decided to launch a project, known as EIRENE (European Integrated Railway Radio Enhanced Network), to determine the functional and system requirements for supporting GSM in a railway environment (that is GSM-R). The project was concluded in 2000 and the architecture of the GSM-R system was largely adapted from the 3GPP Release version 1999 specifications [26].

The GSM-R specifications developed from the EIRENE project have been prevalently adopted globally by railway agencies, as the platform, for supporting mobile coverage in a railway environment. In [27], it was optionally specified that the expected handover success rate for the GSM-R system was at least 99.5%. It also provided information that the current best estimate for handover execution is 300 ms in GSM-R and that a break of 10 s in services would be deemed unacceptable.

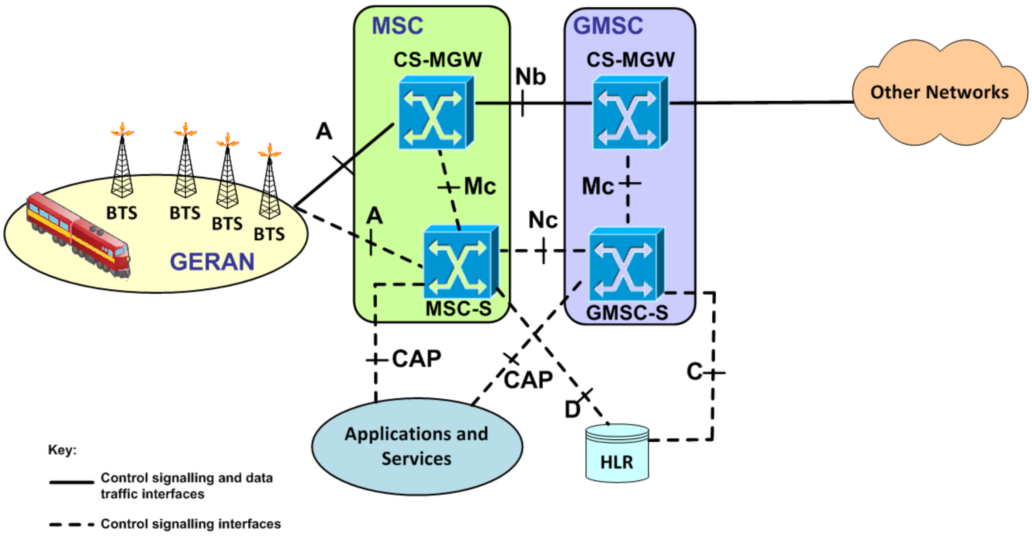

Figure 2-3: GSM-R CS Core Network Architecture

In the 3GPP Release 8 specifications, an all-IP based core network architecture, also known as Evolved Packet Core (EPC) was envisaged. Therefore, prior to the availability of the Release 8 standards, changes in the CS domain of the core network to support IP-based functionalities in GSM-R were implemented. This was addressed in the Release 4 specifications, [26], and the MSC was replaced by a coupled MSC server (MSC-S) and Circuit Switched-Media Gateway (CS-MGW). The MSC-S is responsible for the call control and mobility management functions, whereas the CS-MGW is controlled by the MSC-S and is in-charged of user's data. Also in [26], the GMSC functionalities was replaced by the following two entities, GSMC server (GMSC-S) and CS-MGW, as shown in Figure 2-3.

The progress towards the support of an all-IP network for 4G and beyond communication system in a railway environment is further validated with the UIC updating the EIRENE functional and system requirement specifications, see [28] and [27]. The updated specifications takes into account the ETSI Release 4 network architecture specified in [21].

2.2.2 Wireless LAN

2.2.2.1 Overview

In 1997, the IEEE approved the original 802.11 standard for Wireless Local Area Network (W-LAN) technology. This technology provided data rates of 1 Mbit/s and 2 Mbit/s, using three different wireless technologies: Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS), and Infrared (IR). In 1999, the IEEE ratified the 802.11a and 802.11b standards.

The IEEE 802.11a standard provides operation in an unlicensed frequency band at 5 GHz and is able to accommodate data rates of up to 54 Mbit/s. To achieve a data rate of 54 Mbit/s, 802.11a uses Orthogonal Frequency Division Multiplexing (OFDM) for transmission.

The IEEE 802.11b standard is an extension of the original IEEE 802.11 standard, also known as WiFi. It operates in the 2.4 GHz Industrial Scientific and Medical (ISM) spectrum and is capable of providing data rates up to 11 Mbit/s using DSSS. This extension is backwards compatible with the original 802.11 standard (only DSSS systems; not FHSS or IR Systems) but adopts a Complementary Code Keying (CCK) modulation technique, which allows an increase in data rate [29].

In March 2007, the 802.11-1997 standard was revised and updated with the eight amendments (IEEE 802.11 a, b, d, e, g, h, i, and j) that were approved by the IEEE. It was published as IEEE 802.11 – 2007. One of the significant revisions was the IEEE 802.11g amendment [30], that was approved in June 2003. The amendments enable higher data rates of up to 54 Mbit/s to be supported, while maintaining compatibility with the deployed 802.11b equipment. It specified operation in the same 2.4 GHz frequency band and with the same DSSS modulation types as 802.11b at rates up to 11 Mbit/s, while adding more efficient OFDM types at higher speeds up to 54 Mbit/s. Further amendments to [31] have since been published and include the ratified IEEE 802.11n and 802.11p standards.

IEEE 802.11n introduces enhancements to the PHY and MAC layer and supports a minimum throughput of 100 Mbit/s. To achieve higher throughput (HT) performance, the PHY modifications in [32], include MIMO techniques, spatial multiplexing, spatial mapping with transmit beamforming, space-time block coding (STBC), low-density parity check (LDPC) encoding and antenna selection (ASEL). Additional MAC functionalities specified in [32], included frame aggregation, enhanced block acknowledgement, power save multipoll (PSMP) operation reverse direction (RD) and protection mechanisms for ensuring compatibility with older versions of mobile devices that do not support functionalities defined in [32]. Further descriptions of the enhancements are elaborated in [32].

Recent developments to enable Wireless Access in a Vehicular Environment (WAVE) were defined by the 802.11 work group. The IEEE 802.11p specification [33] was approved in June 2010, operating within the licensed 5.9 GHz frequency band that was defined as Dedicated Short Range Communications (DSRC) spectrum band by the Federal Communications Commission (FCC) in the United States. The frequency band was allocated by the FCC for dedicated usage in Intelligent Transportation Services (ITS), which enables communication between vehicles and also infrastructure-to-vehicle interaction [34, 35]. The IEEE 802.11p specification describes additional functionality and service modifications that are necessary to allow the workability of mobile devices in ever changing vehicular conditions. Moreover, enhancement to the signalling techniques and the interface for enabling communication with mobile devices that are not within the coverage area of the basic service set (BSS) were also considered [33].

2.2.2.2 W-LAN Spectrum Utilisation

In this section, the widely deployed W-LAN in the 2.4 GHz frequency band is discussed. As stated in [31] and shown in Figure 2-4, the RF (Radio Frequency) spectrum is divided into 14 channels. Moreover, in Europe, USA, China and Japan, the High Rate PHY operates in the 2.4-2.4835 GHz band. In Japan, it can also operate in the 2.471-2.497 GHz band. The FCC allows the use of 11 channels in the 2.412-2.462 GHz band. The ETSI regulatory body conforms to the FCC (US) channel assignments with the exception that channels 12 and 13 are allowed. Some countries in Europe have unique channel restrictions. France allows operation from channel 10 to 13 and Spain allows operation from channel 10 to 11. Since the FCC (US), IC (Canada) and ETSI (Europe) specify that the operation bandwidth is only 83.5 MHz and that different channels can operate simultaneously without interference if the distance between the centre frequencies is at least 25 MHz, only three channels can be used simultaneously [31].

CHNL_ID	Frequency (MHz)	Regulatory Domains							
		FCC (USA)	IC (Canada)	ETSI (Europe)	Spain	France	Japan	Japan	China
1	2412	✓	✓	✓	—	—	—	✓	✓
2	2417	✓	✓	✓	—	—	—	✓	✓
3	2422	✓	✓	✓	—	—	—	✓	✓
4	2427	✓	✓	✓	—	—	—	✓	✓
5	2432	✓	✓	✓	—	—	—	✓	✓
6	2437	✓	✓	✓	—	—	—	✓	✓
7	2442	✓	✓	✓	—	—	—	✓	✓
8	2447	✓	✓	✓	—	—	—	✓	✓
9	2452	✓	✓	✓	—	—	—	✓	✓
10	2457	✓	✓	✓	✓	✓	—	✓	✓
11	2462	✓	✓	✓	✓	✓	—	✓	✓
12	2467	—	—	✓	—	✓	—	✓	✓
13	2472	—	—	✓	—	✓	—	✓	✓
14	2484	—	—	—	—	—	✓	—	—

Figure 2-4: High Rate PHY Frequency Channel Allocation

The channel centre frequencies and CHNL_ID number are shown in Figure 2-4. Table 2-1 shows the two different sets of European operating channel selection: set 1 consists of three non-overlapping channels and set 2 consists of seven overlapping channels. The European channel selections without and with overlapping are shown in Figure 2-6 and Figure 2-7 respectively.

Set	Number of channels	HR/DSS channel numbers
1	3	1, 7, 13
2	7	1, 3, 5, 7, 9, 11, 13

Table 2-1: European operating channels (excluding France and Spain)

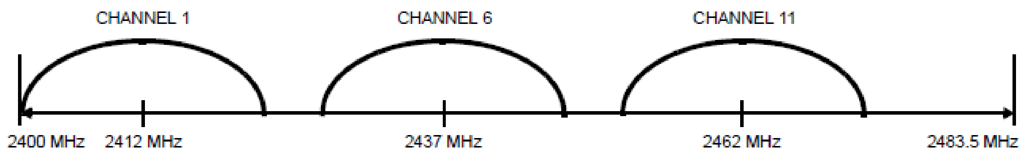

Figure 2-5: China and North American Channel Selection without overlapping [31]

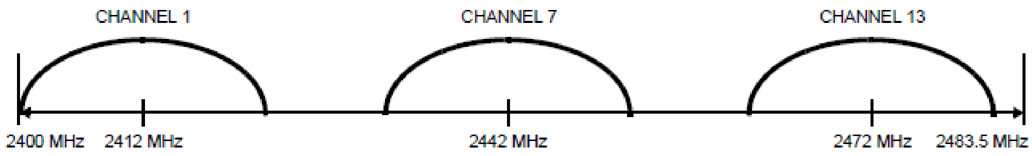

Figure 2-6: European Channel Selection without overlapping [31]

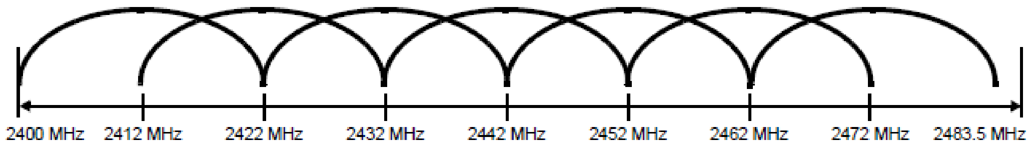

Figure 2-7: European Channel Selection with overlapping [31]

2.2.2.3 W-LAN Architecture

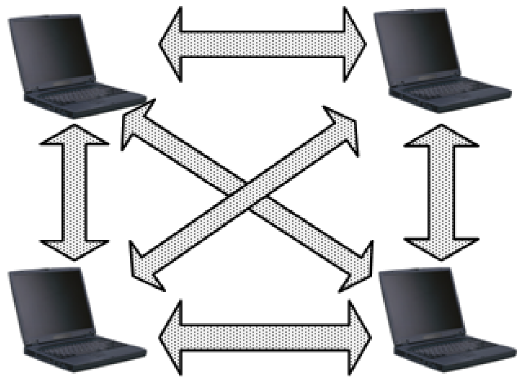

Figure 2-8: IBSS

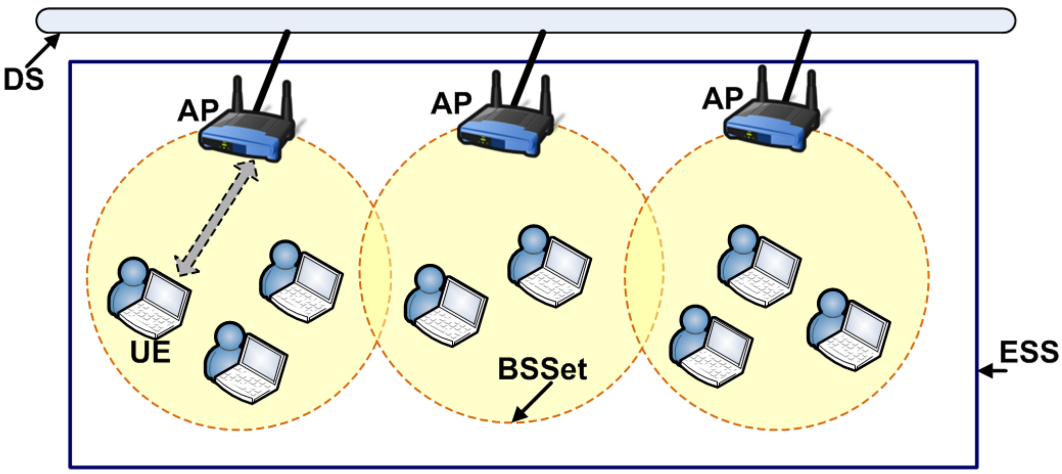

Figure 2-9: ESS

The W-LAN architecture consists of the following main components: Basic Service Set (BSS), Access Point (AP), Distribution System (DS), Extended Service Set (ESS) and W-LAN mobile device. In both BSS and ESS, the W-LAN terminals will communicate through an AP. The network topologies are described as follows:

Independent Basic Service Set (IBSS): The IBSS configuration, as shown in Figure 2-8, is an ad-hoc network containing a set of W-LAN mobile devices that communicate directly with one another on a peer-to-peer basis without using an AP or any connection to a wired network.

Basic Service Set (BSS): The coverage area of the BSS is known as basic service area (BSA). A W-LAN mobile device that is within the BSA is able to communicate via the AP, but no direct communication would be available once the mobile device leaves the BSA.

Extended Service Set (ESS): This consists of several overlapping BSSs, which are connected together by the DS (Distribution system) and each BSS should have an AP or Portal. W-LAN mobile devices within the ESS are able to communicate with each other and roam between the BSSs. This is transparent to the logical link control (LLC) layer and is illustrated in Figure 2-9.

2.3 Heterogeneous Networking Literature

2.3.1 Satellite and UMTS Systems

The 3GPP Release 12 specifications mentions about interworking between the Evolved Packet System (EPS), also known as 4G, with 3GPP and non-3GPP access systems and shown in Figure 2-10 [36]. However, it is noted that interworking with non-3GPP systems, such as satellite systems, were not explicitly defined. It is foreseeable that satellite systems would also play an important role for systems beyond 4G. Therefore, interworking between a mobile and satellite system will be addressed in this section, which will be based on the Satellite-UMTS (S-UMTS) system.

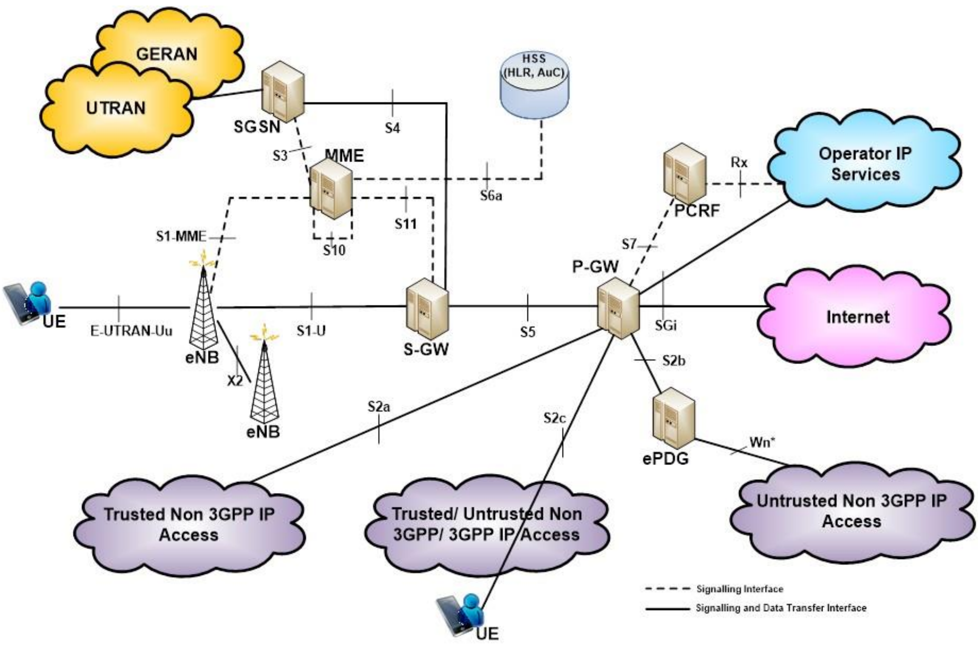

Figure 2-10: EPS Architecture with Other Access Networks

The ITU originally approved five main proposals on the definition of the terrestrial network of IMT-2000 and six different proposals for the satellite component [37]. Universal Mobile Telecommunications System (UMTS) is part of the IMT-2000 family and Satellite-UMTS (S-UMTS) is an integral part of UMTS. In S-UMTS, the access network domain consists of the USRAN (UMTS Satellite Radio Access Network), which is the interface between the user domain and the UMTS Core Network (CN). The overview of the S-UMTS concept is presented in Figure 2-11. It is envisaged that the integration of S-UMTS and Terrestrial-UMTS (T-UMTS) will provide several advantages, such as [38]:

- Seamless service provision;
- Re-use of terrestrial infrastructure;
- Highly integrated multi-mode user terminals;
- Backup or main service coverage for areas where terrestrial cellular systems are unfeasible.

In addition, S-UMTS services can complement T-UMTS services in two ways [38]:

- **Geographic extension services**: where the USRAN is used to provide extended geographic coverage for UMTS services. This includes: telephony for maritime and aeronautical users; remote surveillance of high value objects, e.g. pipelines and industrial plants in hard to access regions; news gathering and database access for journalists operating in remote parts of the world; tele-diagnostic in emergency cases; and, many other telemetry applications.

- **Functional extension services**: where the USRAN is used to provide services that extend the functionality of UMTS services. These services may be used to complement other services provided by either a USRAN or a UTRAN (UMTS Terrestrial Radio Access Network). This category includes multicast and broadcast services, which cannot be efficiently provided by T-UMTS.

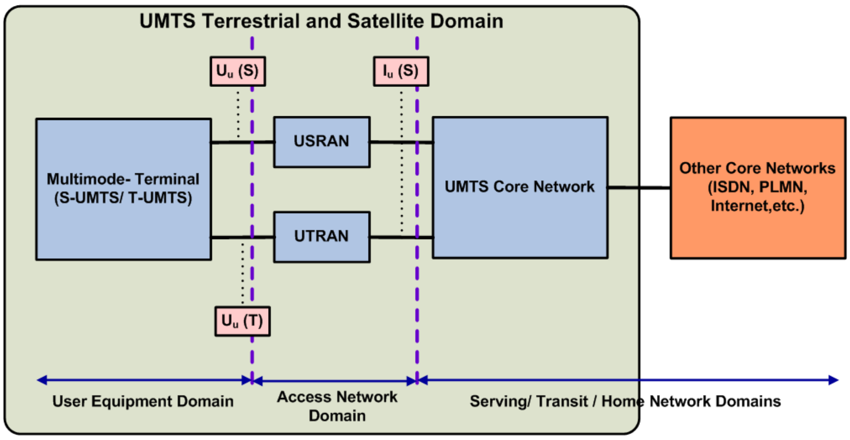

Figure 2-11: Overview of Satellite-UMTS concept

The S-UMTS architecture can be split into the space segment, user segment and ground segment. The space segment can be further broken down into Geostationary Earth Orbit (GEO) or Non-GEO satellites, such as Low Earth Orbit (LEO) satellites, and classified as single-hop or double-hop, bent-pipe or regenerative satellite and ISL (Inter-Satellite Links) or non-ISL. The user segment consists of the User Equipment (UE), and the ground segment is made up of the Network Control Centre (NCC)s, gateway(s) and inter-site communication facilities. This is further elaborated in [38].

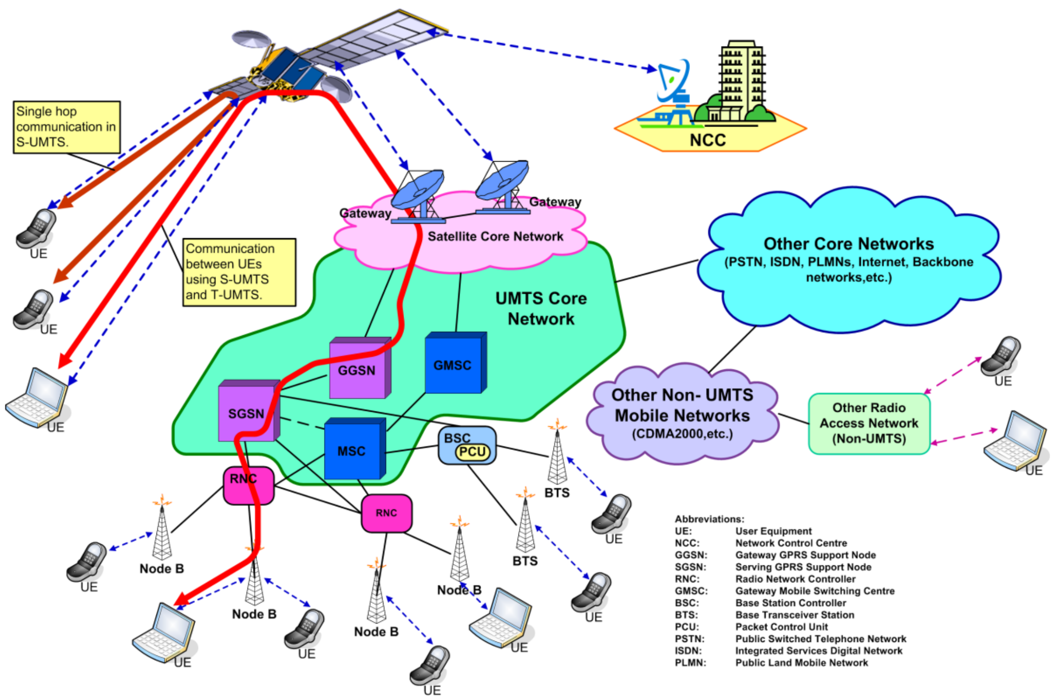

Figure 2-12: Satellite-UMTS and Cellular System Scenario

An example scenario of S-UMTS integration with cellular systems and a “GEO satellite, single-hop S-UMTS” model is depicted in Figure 2-12. For S-UMTS, the gateway provides the same functionalities as the radio network controller (RNC) and Node B (base station) components in T-UMTS. For a UE to route traffic through the S-UMTS and cellular system, it must be S-UMTS, T-UMTS, GPRS and GSM compliant. For the “single-hop, GEO satellite, S-UMTS” scenario, the satellite segment performs the access functions and is also expected to have some routing functionalities. This is because the satellite segment is required to route information in a single-hop between two UEs without having to go through the UMTS CN. To support this additional functionality, which was usually performed by the UMTS Core Network, it will require the Uu- and Iu- interface to be modified. This is further addressed in [38]. In limited satellite coverage or indoor regions, an Intermediate Module Repeater (IMR) can be implemented to reamplify and propagate traffic between the satellite and UE, as shown in Figure 2-13. Several IMR solutions are address in [39], such as:

- **On-Channel Repeater**

  This type of repeater receives the satellite signal in the MSS (Mobile Satellite Service) band, amplifies the signal before forwarding it on the same frequency slots(s).

- **Frequency Conversion Repeater**

  For this repeater, the satellite signal is received in the FSS (Fixed Satellite Service) frequency band, amplified and frequency converted before forwarding in the MSS band.

Other IMR solutions, such as Node B-based repeater and Evolved Node B-based repeater, are further elaborated in [39].

The delivery of MBMS via satellite (i.e. S-UMTS) is addressed by the ETSI S-MBMS (Satellite Multimedia Broadcast Multicast Service) workgroup [40]. S-MBMS is a unidirectional point-to-multipoint bearer service in which data is transmitted from a single source entity to multiple recipients [40]. Two types of bearer service are supported by S-MBMS: broadcast mode and multicast mode. For both modes, S-UMTS is one of the main components responsible for the transmission of multimedia data. Moreover, S-MBMS user services are classified according to the methods that are used to distribute the services. Three main types of user service are identified [40]:

- **Streaming Services:** This type of service focuses on supporting continuous stream of traffic carrying media (i.e. audio and video) data and is a basic S-MBMS user service requirement. It also takes into consideration the delivery of static media (i.e. still images), whereby the static media needs to be synchronised and displayed with audio/video streams.

- **File Download Services:** This service supports the delivery of binary data over a S-MBMS bearer. Reliability is an important factor for this type of service. The user needs to receive all data that is sent in order to experience the service. Two types of download scheme are specified: Batch (cold) and Urgent (hot) download.
- **Carousel Services:** This type of service is a combination of both the Streaming and File Download services. Similar to streaming services, this type of service takes into consideration time synchronisation but its expected media of service is only static media. As with file download services, reliability is also an important factor for this type of service. However, it is not expected to have 100% reliability. An advantage of this service is that it can be delivered over a low bit-rate bearer.

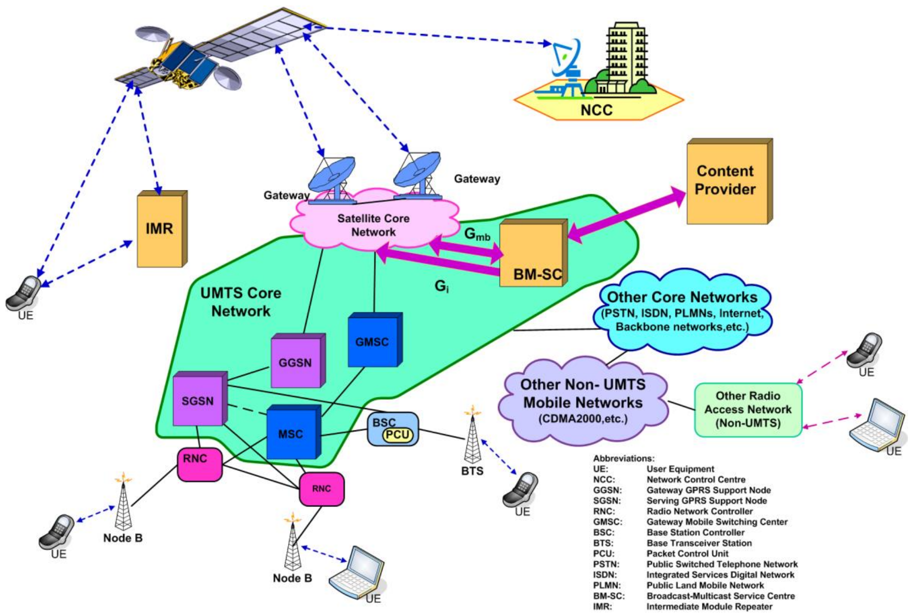

Figure 2-13: Example Architecture to support satellite MBMS (S-MBMS)

An example scenario is depicted in Figure 2-13. The BM-SC (Broadcast Multicast-Service Centre) provides functions for S-MBMS UE service provisioning and delivery. For example, it controls UE access to services, authorises and initiates bearer services within the network, and schedules and transmits MBMS data across the network [41]. A summary of the functions supported by the BM-SC is provided in Figure 2-14. The architecture and functional description and service scenarios are further elaborated in [39] and [40].

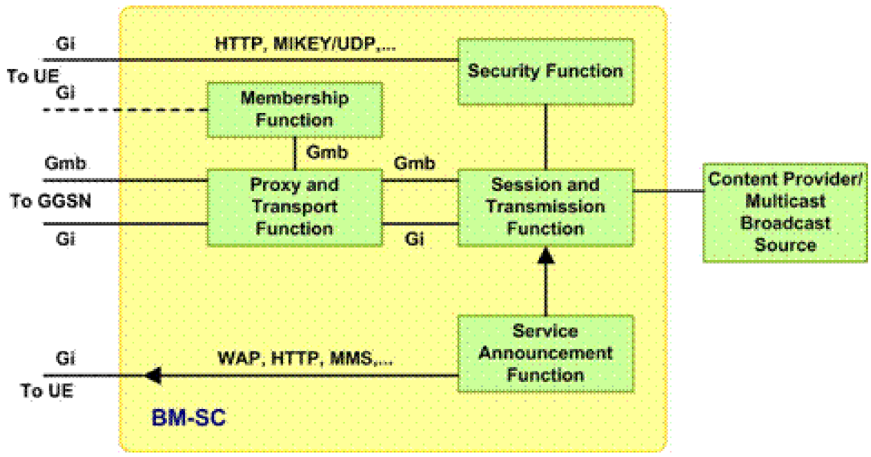

Figure 2-14: BM-SC functionalities

2.4 The Internet Phenomenon

2.4.1 Internet Protocol (IP)

The Internet is made up of routers that are responsible for the routing and forwarding of the IP packets to the designated host. If the final destination of the packet is not within the host's network, the packet will then be forwarded through the Internet (which could be through different wireless or wired technologies) until it reaches its designated host. However, the path or route that the packet travels from the host to the designated host is determined by the routing algorithm used, such as routing information protocol (RIP) or open shortest path first (OSPF), and is elaborated in [42]. The two basic versions of the IP protocol (i.e. IPv4 and IPv6), which have been standardised by the Internet Engineering Task Force (IETF), will be briefly described below:

- *IPv4*

  In IPv4, an IP address is 32- bits long; hence, a total of 2^{32} possible addresses can be assigned. Every host or router that is connected to the Internet is assigned at least one IP address, which is necessary for the forwarding and routing of IP packets. In the IPv4 header, the Source Address is the host's source address and Destination Address is the designated host address, both of which remain unchanged throughout the transmission of the packet from the source host to the designated host. Further detailed descriptions of these different fields, IP addressing and routing are elaborated in [42-44].

- *IPv6*

  The exponential growth of the Internet is causing a strain on the current IPv4 protocol to provide sufficient addresses to support user demand. Thus, the main reasons for the development of the IPv6 protocol are to alleviate this issue and to benefit future peer-to-peer applications and mobile networking.

  IPv6 has addressed several limitations of IPv4. Some of the advantages of IPv6 are it has a larger address space (i.e. an IPv6 address is 128-

bits long); it consists of a better header format (so as to simplify and speed up the routing process), support for resource allocation (to enable better Quality of Service (QoS) support that can be used for transmission of real-time audio and video traffic) and better security support [42]. With IPv6, a total of 2^{96} possible addresses can be assigned and with this expanded addressing capability, it can be ensured that the amount of IP addresses will not run out anytime soon. However, to support the IPv6 protocol, several protocols that inter-worked with IPv4 were updated, such as internet control message protocol (ICMP) and domain name system (DNS). In addition, to allow more functionality in IPv6, six extension headers (i.e. Hop-by-Hop Option, Routing, Fragmentation, Authentication, Encapsulated Security Payload and Destination Options) were introduced and are elaborated in [45-47].

IP has become so widely deployed these days. As the number of Internet users has increased, it has become increasingly important to consider supporting IP for future technologies. This is evident through the on-going work that is taking place in the 3GPP. For instance, in the 3GPP Release 8 specification, issues with regards to the migration towards an all-IP core network, known as Evolved Packet Core (EPC), for cellular systems were addressed. The EPC plays a crucial role in integrating the “True 4G” technologies, i.e. WiMAX-Advanced and LTE-Advanced (defined in the 3GPP Release 10 onwards specifications). Another example is the transmission of IP packets through DVB satellite systems (e.g. DVB-S, DVB-S2 and DVB-RCS), which uses the MPEG-2 transport stream for data transmission. Multi-Protocol Encapsulation (MPE) and Ultra Light

Encapsulation (ULE) are two methods used for the encapsulation of IP packets for transmission over the MPEG-2 transport stream [48, 49]. Most current and planned satellite systems already support IPv4 and many research activities contributed towards the development and standardisation of the associated networking aspects [50-52].

As stated in [53], IPv6 introduces additional features, such as stateless auto configuration, duplicate address detection (DAD), router and prefix discovery, which requires bi-directional links and would pose a challenge for satellite networks. This was also further specified in [54]. To support the full capability of IPv6 for DVB satellite systems, several issues still need to be resolved for future development.

In the meantime, there has been considerable research and development in terrestrial telecommunications devoted to preparing for the transition from IPv4 to IPv6 networks, namely looking into supporting IPv6 for future systems. However, much research work on IPv6 networks has mainly focused on terrestrial radio access networks (RANs) and only a handful have considered supporting IPv6 within satellite systems. 4G is seen as a convergence of different broadband wireless systems and it is deemed necessary and crucial for IPv6 to be taken into consideration for satellite systems, as successful deployment of a heterogeneous network for 4G depends on the interworking between the different access technologies. IPv6 is planned as part of a work item in the ETSI BSM (Broadband Satellite Multimedia) workgroup (WG) [51] and will support IPv6 protocols using the satellite independent network interface [52]. The WG has carried out reviews on transitioning and supporting IPv6 for satellite networks, which is available in [54]. The outcome from the review highlighted that research developments focused mainly on supporting IPv4 networking and recommended the need for further work in supporting IPv6 in BSM. Other research initiatives that had contemplated IPv6 in satellite systems are North Atlantic Treaty Organisation's (NATO) education programme project, SILK, and SATIP6 (an EC fifth framework programme (FP5) project) that assessed the issues in deployment of IPv6 over DVB-RCS.

2.4.2 Review of IPv4 to IPv6 Migration Strategies

The exponential growth of the Internet is causing a strain on the current IPv4 protocol to provide sufficient addresses to support user demand. Thus, the main reasons for the development of the IPv6 protocol are to alleviate this issue and to benefit future peer-to-peer applications and mobile networking.

The deployment of an "all new IPv6" infrastructure is an arduous task due to factors such as the cost, scalability and time. Therefore, it has been widely accepted that IPv6 will be introduced to the existing IPv4 infrastructure, and to enable seamless introduction, migration strategies will be adopted. In this way, it will minimise any impact on existing network users [55].

Migration strategies consist of three main transition mechanisms: Dual Stack, IPv6 tunnelling mechanisms and IPv6 translation mechanisms.

Dual Stack

An "IPv4-IPv6 node" (e.g. the operating system of a host, router) is equipped with both sets of protocol stacks (although in practice, the stacks share many elements) and this allows the node to send/receive both IPv4 and IPv6 packets [56]. An example is illustrated in Figure 2-15, whereby IPv4 and IPv6 islands can send and receive IP packets with the aid of a router that supports both IP protocols (i.e. the Dual Stack Router and Dual Stack Edge Router). The advantage of dual stack mechanisms is that IPv4 and IPv6 share the same network - this implies that there is no need to design new routers specifically for IPv6.

The Dual Stack is the widely preferred IPv6 transition approach and has also been addressed for BSM systems. Details on dual stack for BSM systems are specified in [54]. For further information regarding Dual Stack, refer to [55, 56].

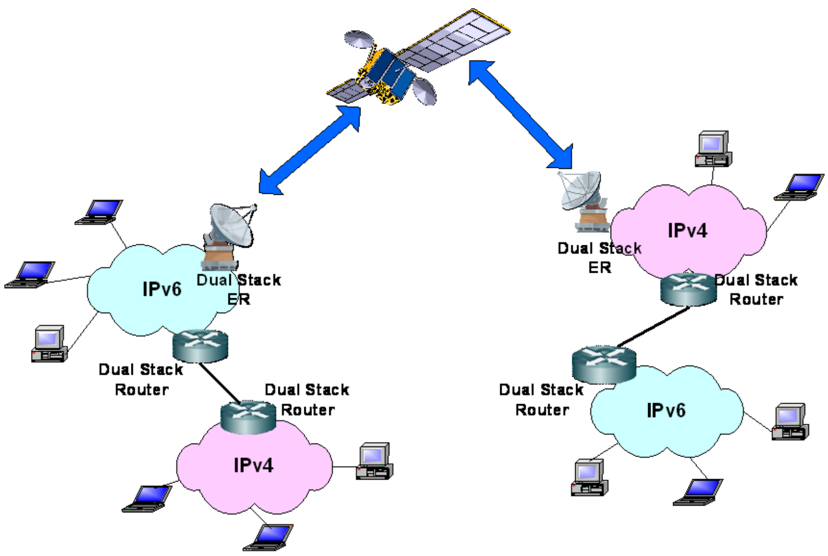

Figure 2-15: Migration of IPv4 to IPv6 – Dual Stack

IPv6 Tunnelling Mechanisms

Tunnelling mechanisms for channelling IPv6 packets over IPv4 networks can be configured either manually or automatically. The tunnelling can be either encapsulation of IPv6 packets in IPv4 packets or vice versa. There are several tunnelling methods available; as listed below:

- *Configured Tunnel*

  This type of tunnel is most suitable when supporting external IPv6 connectivity to a whole network. It is stated in [56] as IPv6-over-IPv4 tunnelling, whereby the IPv4 tunnel endpoint address is determined by configuring information on the encapsulating node. Furthermore, the tunnels can be bi-directional or uni-directional.

- *Tunnel Broker*

  Tunnel broker is appropriate for small isolated IPv6 islands and isolated IPv6 users in an IPv4 network that wish to establish connectivity to an IPv6 network. The function of the tunnel broker is to automatically manage IPv6 tunnels and to tunnel requests from isolated IPv6 sites on behalf of one or more dedicated servers [57].

- *IPv6 over ATM and MPLS*

  The employment of Asynchronous Transfer Mode (ATM) transitioning to IPv6 is similar to Multiprotocol Label Switching (MPLS). Both use an overlay network model, whereby the core network elements are capable of handling encapsulated IPv6 packets without requiring knowledge of IPv6. Only the edge network devices need to be IPv6-aware [55].

- *6to4*

  This method is suitable for isolated IPv6 islands to communicate via the IPv4 network without using explicit tunnels. It treats the IPv4 network as a unicast point-to-point link layer, specifying an encapsulation mechanism for transmitting IPv6 packets over the Internet by assigning a unique IPv6 address prefix to any site with at least one globally unique IPv4 address [55]. This method is not intended as a permanent solution, but as a start-up transition tool during the co-existence of IPv4 and IPv6 [58]. An example diagram is depicted in Figure 2-16 and a detailed description of this method is provided in [58].

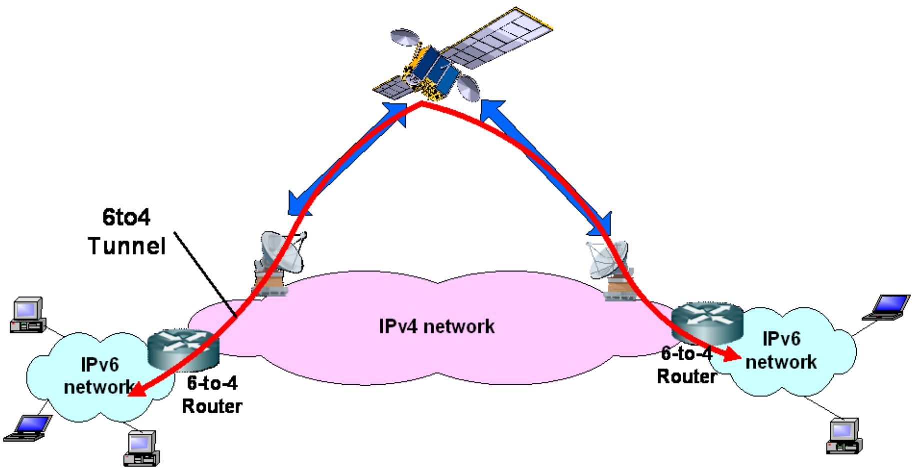

Figure 2-16: Migration of IPv4 to IPv6 – 6to4 tunnelling

- *Intrasite automatic tunnel addressing protocol (ISATAP)*

  Due to the insufficient support for IPv4 multicasting in ISP networks, this method is proposed as an alternative option to 6over4[1]. ISATAP is designed to connect isolated IPv6 hosts and routers (nodes) within an IPv4 site [59]. Furthermore, it employs the site's IPv4 infrastructure as a virtual link, but it does not use IPv4 multicast,

[1] 6over4 is another tunnelling method that allows isolated IPv6 hosts, located on a physical link, which has no directly connected IPv6 router, to become fully functional IPv6 hosts by using an IPv4 domain that supports IPv4 multicast as their virtual link [58]. However, it is not widely adopted and will not be further elaborated.

therefore the link is Non-Broadcast Multiple Access (NBMA). This method is capable of enabling automatic tunnelling, irrespective of whether global or private IPv4 addresses are used.

Further information on other tunnelling mechanisms, such as Teredo, Dual Stack Transition Mechanism (DSTM), Tunnel Setup Protocol, OpenVPN-based tunnelling solution, IPv6 over ATM and MPLS, can be found in [55, 57, 60-62] respectively. The use of tunnelling approaches for BSM systems, such as configured tunnel, 6to4 and 6over4, are specified in [54].

<u>IPv6 Translation Mechanisms</u>

It is necessary to use translation mechanisms to allow an IPv6-only node to communicate with an IPv4-only node. The following lists some translation methods:

- *Stateless IP/Internet Control Message Protocol Translation (SIIT)*

  SIIT specifies a key translation algorithm for enabling interoperation between IPv6-only and IPv4-only hosts [63]. An IP datagram travels through the SIIT translator, and it converts the datagram headers between IPv4 and IPv6, with the aid of temporary assigned IPv4 addresses.

- *Network Address Translation-Protocol Translation (NAT-PT)/ Network Address Port Translation + Packet Translation (NAPT-PT)*

  NAT-PT, defined in [64], is based on the common IPv4 NAT concept. It can be used to translate IP packets sent between IP-heterogeneous networks, by binding the addresses in the IPv6 networks, and vice versa, to transparently route the IP packets traversing different realms. NAPT-PT extends the concept of NAT-

PT by also translating transport identifier (such as TCP/UDP port numbers, ICMP query identifiers).

- *Bump in the Stack (BIS)/Bump in the API (BIA)*

  BIS is an extreme extension of NAT-PT, in which a pool of IPv4 addresses is dynamically allocated to hosts. BIS adopts a unique translation approach, by moving the translation inside the individual hosts rather than performing the translation at a centralised server. The host is capable of translating between IPv4 and IPv6 internally by including the necessary segments in its IP stack [65]. The BIA translation mechanism is similar to BIS. However, it does not translate the IP headers, on the contrary, BIA inserts an API translator between the host's stack TCP/IP modules [66]. This allows the translation to be performed without the overhead of translating every packet's header [55].

- *Transport Relay Translator (TRT)*

  This translator is located on the transport layer. It relays TCP and UDP connections at the border between IPv4 and IPv6 domains, acting as an intermediary between them [67]. When two hosts (Host A and Host B) attempt to connect through a TRT, two connections are established (i.e. One connection between Host A and the TRT component and the other connection between the TRT component and Host B). Both connections maintain their native protocol, because the TRT performs the necessary translation of the traffic to transparently relay traffic between the two hosts.

- *Application Layer Gateway (ALG)*

ALG is usually a dual-stack device that allows hosts to communicate between IPv6 and IPv4. It does not perform direct translation, but behaves more as a relaying proxy at application layer. Examples of an ALG are a HTTP proxy or SMTP server.

- *SOCKS64*
  In [68], an IPv6/IPv4 gateway mechanism based on SOCKS is presented. This method uses a dedicated SOCKS server for relaying traffic between IPv4 and IPv6 hosts. It extends the application –level of SOCKS 5.0 to allow IPv4 to IPv6 translation. Therefore, SOCKS64 is suitable as an interoperation tool for existing applications that use SOCKS 5.0.

IPv6 translation adopted, i.e. SIIT and NAT-PT, for BSM systems have been briefly discussed in [54]. However, it was also noted that the adoption of IPv6 transition mechanisms for BSM systems would require further work and remains as an important research area to be addressed by the BSM WG.

2.5 Summary

This chapter an overview of the GSM mobile network was presented, including the GSM-R network that is adopted globally by railway operators for wireless communication for nearly a decade. With the shift in paradigm towards packet-oriented services in mobile and wireless communication systems, it is foreseeable that in time, GSM-R will no longer be appropriate to support the future demands for wireless communication in a rail environment and be phased out. However, current functional and system requirements that were specified in the EIRENE standards are useful for determining performance benchmarks, such as handover, for potential replacement systems. This research study looks at employing a satellite-WLAN architecture, which is a possible candidate for substituting GSM-R. Therefore, a background of W-LAN and observations gathered from the S-UMTS system was also discussed.

It is also envisaged that the future replacement system for the rail environment should be capable to support an all-IP end to end network to enable heterogeneity with 4G systems and beyond. Therefore, a background understanding of IP and the migration strategies for IPv4 to IPv6 was deemed necessary and addressed in this chapter.

3 MOBILITY MANAGEMENT

3.1 Scope

The background to mobility management will be described in Section 3.2. Handover management will be addressed in Section 3.2.2, elaborating on the generic handover management model that is shown in Figure 3-2. Within this section, an introduction to the handover management logical processes, handover controlling, connection establishing and connection transference schemes will also be presented.

3.2 Mobility Management

3.2.1 Overview

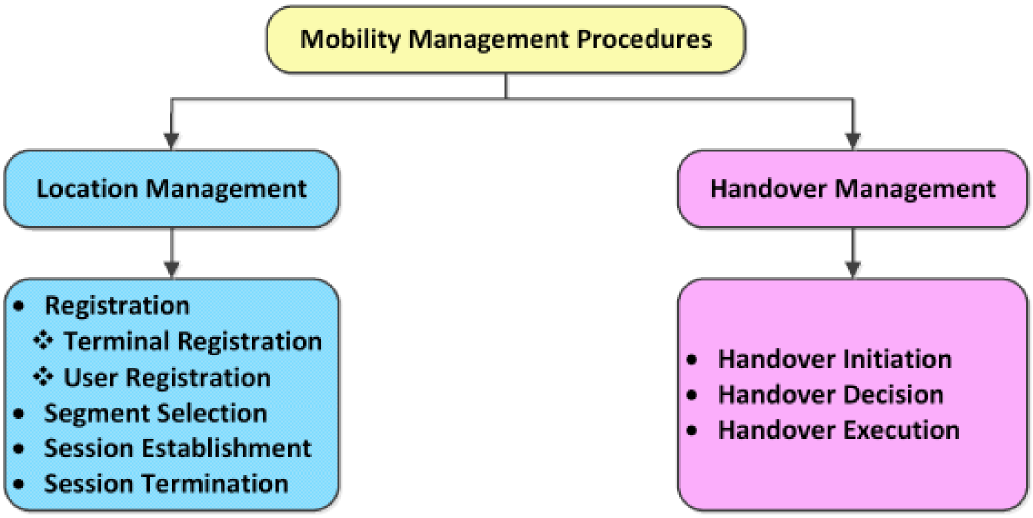

Figure 3-1: Mobility Management Procedures

Mobility management schemes consist of two main procedures: Location Management and Handover Management. This is shown in Figure 3-1. The focus of this research is on handover; therefore the handover management scheme will be addressed in the following sections. For further information on Location Management, see [69] and [70].

3.2.2 Handover Management

3.2.2.1 Introduction

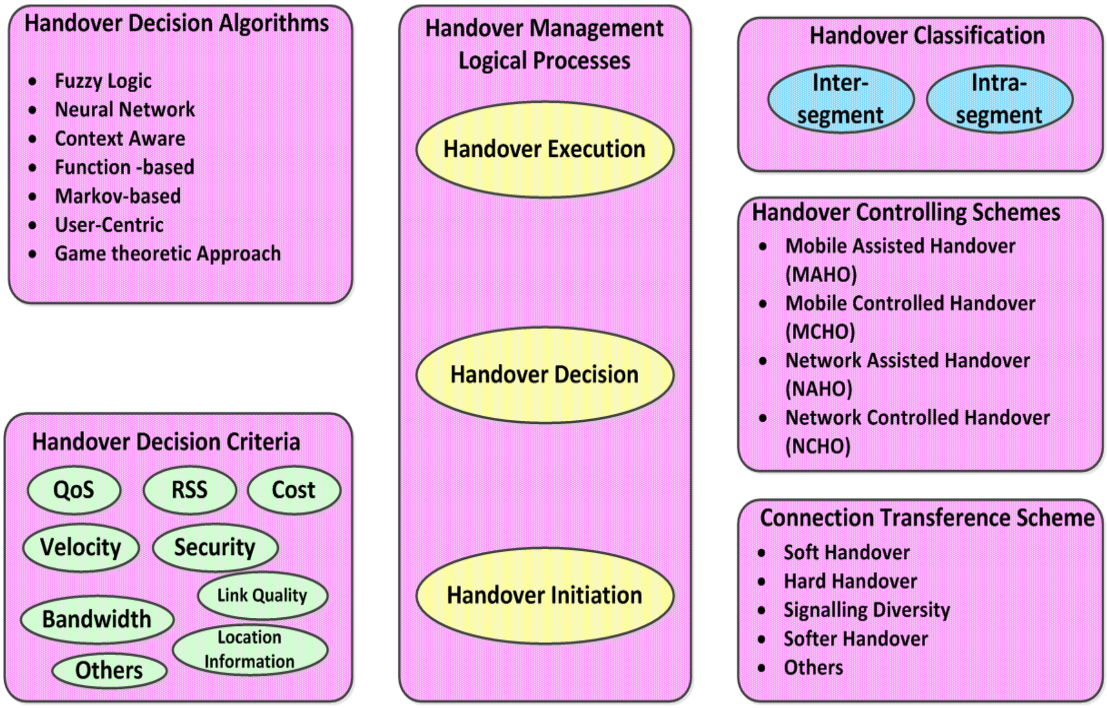

Figure 3-2: Generic Handover Management Model

Handover is the procedure that is initiated when the current network connection of a MN is unable to keep the connection active or if an alternative connection is capable of providing better performance. Handover can be categorised into two main classifications: vertical and horizontal. VHO, also known as inter-segment handover (ISHO), is performed when the MN moves from the network coverage of one access technology to another (such as moving from a satellite access segment to a WiFi access segment). Horizontal handover, also known as intra-segment handover, is performed when the MN moves from one cell boundary to another cell

coverage area within the same access system, for example, handover between the different APs in a WiFi network. This research will concentrate mainly on ISHO of a heterogeneous network. The network comprises WiFi and satellite access segments, based on [69], that are implemented in a high-speed train environment, which will be further elaborated in Chapter 4
.

Based on the handover procedure presented in [71], [72] and [69], handover consists of three main logical processes and is shown in Figure 3-2:

- Handover Initiation (HI)

  This process, also known as handover information gathering or system discovery, determines if handover should be initiated based on the information that is gathered either by the MN or network. For example, the radio link performances of the current and targeted networks are the usual parameters that are widely adopted as the deciding factor for handover to begin. This is based on the measurement of the RSS of the networks and comparing them against the handover threshold. The handover procedure will only be initiated if the RSS deteriorates below the pre-determined threshold value. There have been significant research developments over the years concentrating on designing algorithms or evaluating algorithms for handover initiation, such as those in [73] and [74].

- Handover Decision (HD)

  Handover decision, also known as network or system selection, is the process whereby the network or the MN selects the target point of attachment and the time of the handover [75]. Several handover criteria are considered in a HD procedure, such as end-to-end delay, resources requirements, RSS and user preferences, before a decision is finalised. Research into handover decision algorithms is an on-going, prominent research area, especially algorithms that support heterogeneous networking. For example, in [76], a fuzzy-logic and Analytic Hierarchy Process based HD algorithm was proposed that uses contextual information from the network and terminal for HD. The paper only briefly addressed the approach and details about the HD algorithm, is available in [77]. It is noted that, during handover, the HD algorithm is limited to the end-user's mobile terminal running a single active application; how the algorithm performs when there are multiple active applications were not discussed.

Other approaches that have been employed for HD, such as function-based algorithms, user centric decision algorithm, markov based decision algorithm, game theoretic approach for decision making and NN based algorithms are addressed in [78, 79].

- Handover Execution (HE)

  The HE stage is where the actual handover connection to the targeted network is established and the termination of the bearer connection to the existing network occurs. It is necessary that the MN or end-users should experience the least disruption to services when HE occurs.

3.2.2.2 Handover Controlling Scheme

A handover can be initiated either by the network or the MN. The information gathering process collects information, such as the radio link measurement and availability, and the MN's location. When these measurements are not obtainable, the network or MN cannot proceed with handover. The radio link measurements can be performed by the MN, the network or by both sides. The MN could be responsible for monitoring its location and may be required to feedback this information to the network. Alternatively, the network may already know the location of the MN.

The handover decision may be centralised or decentralised, but only one side of the system can control the handover decision. There are four main handover controlling schemes:

- Mobile Assisted Handover (MAHO)

  In this scheme, both MN and the network perform information gathering. In the case of radio link measurements, the downlink information gathered by the MN is forwarded periodically to the network to enable handover decisions to be carried out by the network. This approach is adopted by the second generation mobile system, GSM, and is noted to have a handover latency of approximately 1 s [80]. However, the network efficiency will decrease if frequent measurements are carried out. This is because frequent measurements will introduce excessive signalling, which will then put a strain on the efficiency of the system.

- Mobile Controlled Handover (MCHO)

In MCHO, the MN has total control of the HD process. The MN is responsible for the information gathering process, which will be used in the decision-making process. This scheme is used in digital cordless telephone systems, such as Digital Enhanced Cordless Telecommunications (DECT). This is a reliable scheme that has one of the lowest handover latencies, which is within the range of 100 to 500 ms [80].

- Network Assisted Handover (NAHO)

  This scheme is the reversal of MAHO. Similar to MAHO, both the MN and network are required to perform information gathering. The network will be required to forward the radio link measurements periodically to the MN, which will be used by the MN in the HD process. This scheme will perform much faster than MAHO and is much more reliable than MCHO. However, there will be an increase in the complexity of the MT and also the signalling load on the radio link.

- Network Controlled Handover (NCHO)

  The network is responsible for the handover decision in this scheme. The network is liable for the information gathering that will be necessary for the decision process. This handover execution time is of the order of many seconds because of the high network load [80]. The NCHO scheme was employed in first generation mobile systems, such as Advanced Mobile Phone System (AMPS).

Further information on the controlling scheme is available in [81].

3.2.2.3 Connection Establishing Scheme

The connection establishing scheme is responsible for establishing a new connection for a MN and disconnecting the old connection. The two types of signalling exchange scheme identified are:

- Forward handover

  When there is an unexpected failure in the current connection, in this scheme the MN must promptly establish a new signalling channel with the targeted connection, i.e. for example from the satellite to a WiFi network or the WiFi network to the satellite. Once the channel is established, the handover signalling exchange is performed. Information stored in the network regarding the previous connection is used to assign the traffic channel on the new connection and to release the radio resources occupied by the previous connection. Location sensors can be used as trigger points during handover.

- Backward handover

  The handover signalling exchange in this scheme is executed through the old connection within the coverage area. This approach has low reliability. This is because if the signal of the old connection is lost before the new connection is established, this will result in the call being dropped.

3.2.2.4 Connection Transference Scheme

The handover execution phase consists of the following classifications:

- Soft Handover

Soft Handover is also known as Diversity Handover. This “make-before-break” scheme utilises additional network resources during handover. It provides seamless handover and does not cause disruption during the handover process because it maintains the current link until the connection to the targeted link is established. There are two different types of classification to this scheme:

1) *Switched Diversity* – At the time of handover, the communication established is only through one of the links and not both concurrently.
2) *Combined Diversity* - The communication is through both of the links simultaneously.

- Hard Handover

  This is a “break-before-make” non-seamless handover. In this scheme the original link is terminated before the new link is established. This would cause disruption and influence the performance of the services.

- Signalling Diversity

  Signalling Diversity is a handover scheme that is adapted from [70]. This scheme, similar to soft handover, is a seamless “make-before-break” handover. Soft handover is not ideal for ISHO, because it would be difficult to implement due to complex synchronisation procedures and long propagation delay differences between the original link and the targeted link. On the other hand, for signalling diversity, the MN is still utilising the current traffic link while signalling procedures are carried out between the MN and the targeted link.

Upon completion of establishing the new traffic link between the MN and the targeted link, the previous signalling and traffic links are terminated. There is no need for synchronisation and the propagation delay difference of the current and targeted access segments is equivalent to the handover break duration.

3.3 Summary

With the on-going development of mobile communications, it can be seen that mobility management will continue to play a significant role in future communication networks. Handover management will remain a crucial and challenging area of research as wireless systems progress into the next generation. In this chapter, a general overview of handover management was presented, which will be helpful in understanding the handover concepts that will be addressed in the following chapters.

4 SYSTEM DESIGN

4.1 Scope

The system design that is adopted for this research study will be addressed in Section 4.2, which is based on the FIFTH project [82]. Based on the system and network architecture, it is necessary to establish the requirements that are required to be taken into account for the functional design of the handover management scheme and this is addressed in Section 4.3. The requirements include resources obtained from standardisation organisations, such as the IEEE, and the FIFTH project. The requirements identified are then used to aid in the proposed handover strategies and functional model approach. The fundamentals of the design methodology are presented in Section 4.5, which defines the FM and information flows (INFs). The FM is then mapped onto the FUA, which is elaborated in Section 4.6.

4.2 System and Network Architecture

The research adopts the overall system architecture from the FIFTH project, which consists of a heterogeneous network employing satellite and WiFi systems to provide Internet services and access to users on a high speed train [69]. The overall architecture comprises the network architecture and terminal architecture that is located on the train.

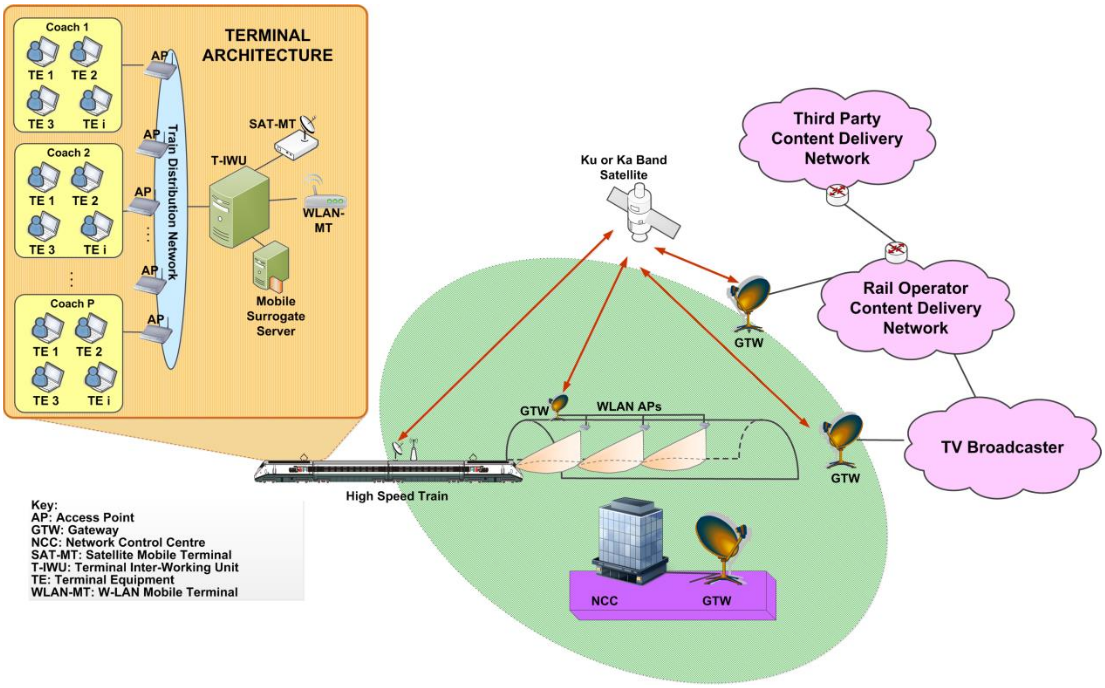

Figure 4-1: Network and Terminal Architecture

The network architecture, shown in Figure 4-1, primarily uses geostationary satellites to provide connectivity and WiFi technology, based on IEEE 802.11b, to extend the satellite connectivity in areas where satellite reception is not possible, such as in a train station. The satellite network is then connected to a Content Delivery Network (CDN), which is used to provide entertainment and communication services to the train via a gateway (GTW).

The terminal architecture, as shown in Figure 4-1, consists of indoor and outdoor sections. The users' terminal equipment (TEs) in the carriage, which are connected to the train's distribution network and then to the T-IWU (Terminal Inter-Working Unit), form the indoor section of the terminal. The TEs could be either the users' own WiFi devices or devices provided by the train operator. The T-IWU is responsible for all mobility and QoS procedures. The T-IWU is connected to the outdoor section that is made up of the satellite and the WiFi terminals, which are also known as satellite and W-LAN mobile terminal (i.e. SAT-MT and WLAN-MT) respectively. In addition, the term mobile terminal (MT) is used to define collectively the SAT-MT, WLAN-MT and the T-IWU of the Multi-Mode Terminal (MMT). The term MMT consists of the SAT-MT, WLAN-MT, T-IWU, APs and the users' TEs in the train carriages. Further information in relation to the WLAN-MT architecture is available in Appendix A.

4.3 System Requirements

Several types of railway environment that a train should encounter, such as open/rural areas and indoor/low-range outdoor areas, need to be considered. The mobility scheme proposed for the system needs to guarantee that end-users should experience minimum disruption to their services on-board high speed trains. Therefore, the following components need to be addressed by the proposed mobility solution:

- Inter-segment mobility management

  This ensures that the MMT is able to provide seamless service connectivity when roaming between the satellite and WiFi access segments[2]. The adoption of location detection procedures to act as

[2] The WiFi access segment can be deployed as an extension of the satellite connectivity, referred to as single-segment access network, therefore handover will only occur between the radio links and will be transparent to the network layer. If the WiFi "hotspot" is used to complement the satellite network, then this is referred to as a multi-segment access network. In this case, during handover, there will be a change in the point of connection of the network. The single-segment access network is the baseline approach that is adopted in this research.

reference points for initiating the MMT's handover procedures is to be determined.

- IP Mobility

  The support of Mobile IP version 6 (MIPv6) with full compatibility with Mobile IP version 4 (MIPv4) is to be taken into account by the system. The baseline requirement for handover is that end-users that are using the system and the MMT should not experience any network layer change and will not require a change in the CoA. However, in the case of a multi-segment access network, there is a change in the point of access and a change to the CoA will need to be addressed.

- User mobility

  This is to ensure that end-users using the system are able to access the entertainment services provided while preserving their own user identity and profile. The user identity and profile information, which can be stored in a smart card, are used for authentication, authorisation and accounting purposes when using the system.

4.3.1 Handover Requirements

Vertical handover, also known as ISHO, is the process that is performed when the current access segment is unable to provide connectivity or if an alternative access segment is capable of a better performance. In this research, the ISHO will be focused on the MT and the handover between the satellite access segment and the extended segment (i.e. W-LAN) in a single access network will be discussed.

As mentioned above, the approach takes into account the RSS of the current and candidate network radio links and geographical location of the MT to aid in the handover procedure. The ISHO procedure will take place within the overlapping region of the satellite and the extended segment. This overlapping region is where the extended segment co-exists with the satellite coverage. From the perspective of the network, there are different types of handover depending on the environment considered namely: (i) tunnel and (ii) train station. The speed of the train and the overlapped region distance are key factors that have to be considered in both scenarios.

Handover in tunnels

The handover procedure in this environment is characterised by the fact that a single-segment access network covers the tunnels' areas. This is shown in Figure 4-2, whereby the gap-filler is implemented by means of W-LAN technology; alternatively, it could be implemented by means of a local satellite repeater.

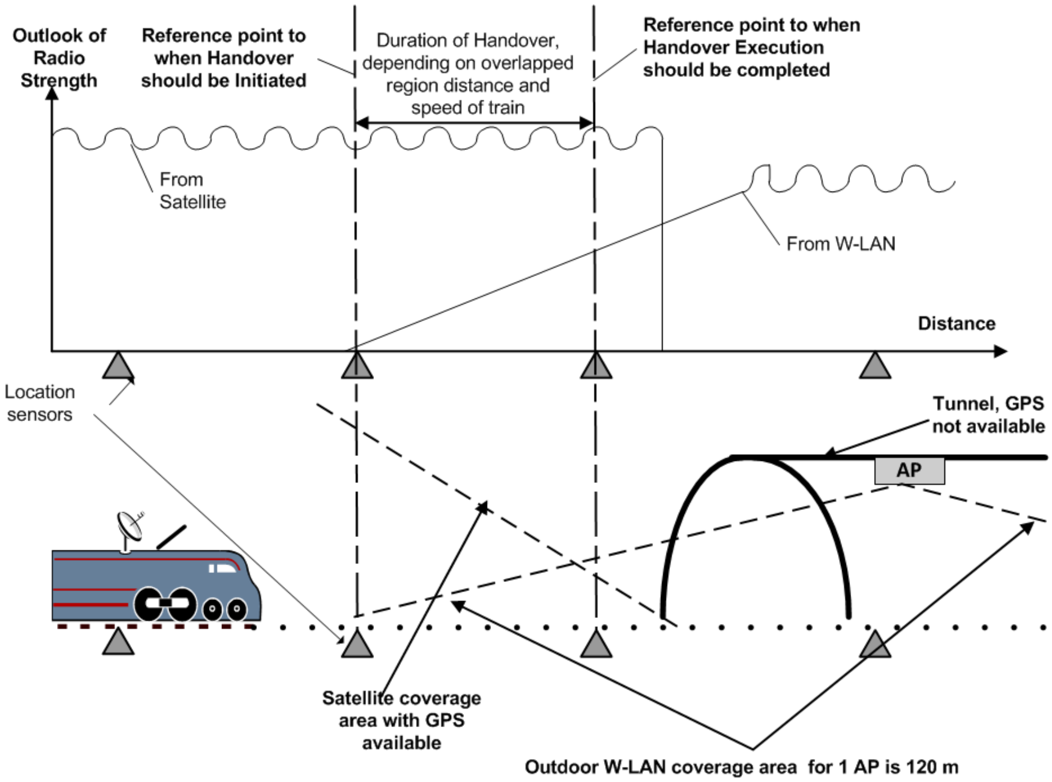

Figure 4-2: Inter-Segment Handover Scenario before Entering the Tunnel

The extended segment is to provide an extension of the satellite link, during ISHO, the network layer functionality is unaffected - handover occurs at the link layer. During the link layer handover execution, procedures such as the transfer of control data, bearer set-up and release, bearer switching, route set-up and release etc. should be conducted. The MT can perform signal measurements to be aware of the radio link availability and also check for the available resources.

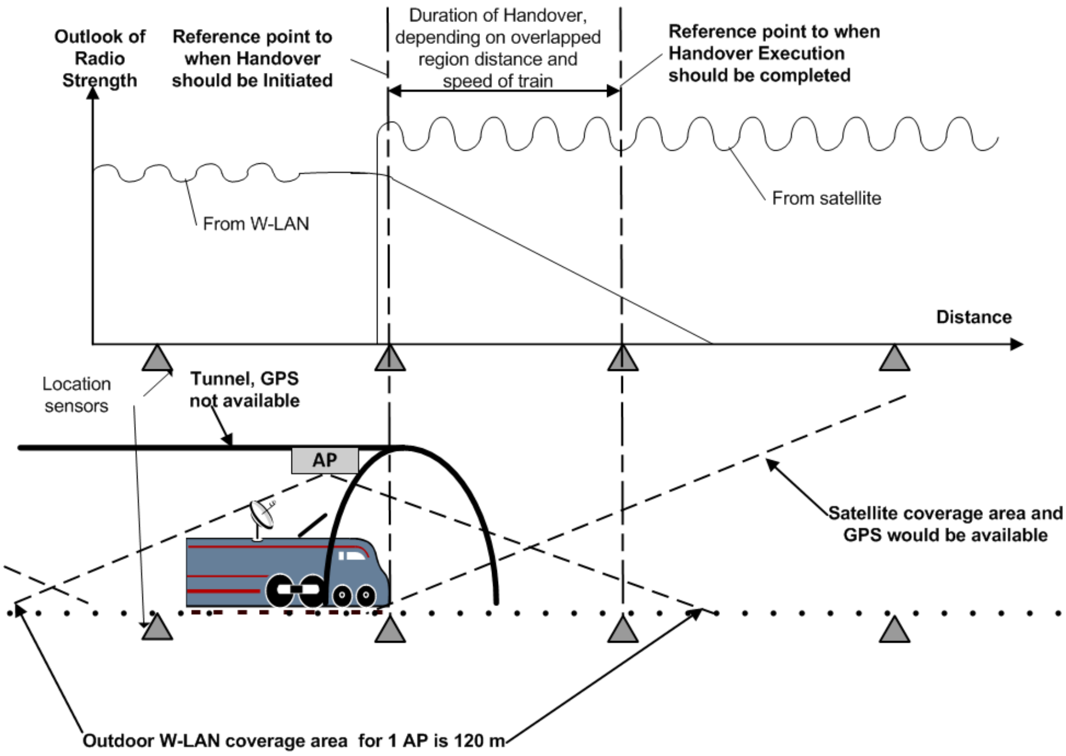

Figure 4-3: Inter-Segment Handover Scenario before Exiting the Tunnel

For handover in a tunnel environment, the speed of the train and the length of the tunnel are factors that have to be considered. The utilisation of location detection procedures (see Figure 4-2 and Figure 4-3) and antenna diversity could extend the time duration provided for handover. For example, this could be achieved by implementing two sets of W-LAN, and satellite antennas on the front and the back of the train, as illustrated in Figure 4-4. Two cases regarding antenna diversity maybe considered depending on the way the gap filler is implemented within the tunnel:

- W-LAN implemented in Tunnels: The train upon entering a tunnel would use the W-LAN antenna at the front of the train and the satellite antenna at the back. Upon exiting the tunnel, the switching configuration would be reversed for both the W-LAN and satellite antenna.

- Local satellite repeaters implemented in tunnels: When the tunnel is longer than the length of the train, a Ku/Ka Band to local repeater (i.e. gap filler) handover should be performed. For the handover process, the train would use the gap filler antenna at the front of the train and the Ku/Ka Band satellite antenna at the back. While establishing the local satellite repeater radio signal, the Ku/Ka Band satellite antenna should be used to maintain the services provided. When handover is completed, the train should be utilising the gap filler antenna. Upon exiting the tunnel, the switching configuration would be reversed for both the gap-filler antenna and Ku/Ka Band antenna.

Furthermore, antenna diversity could alleviate the need to perform handover in tunnels that are shorter than the length of the train. In this example, switch diversity is used to optimally select the most appropriate antenna depending on the availability of the link, but combination techniques could also be employed.

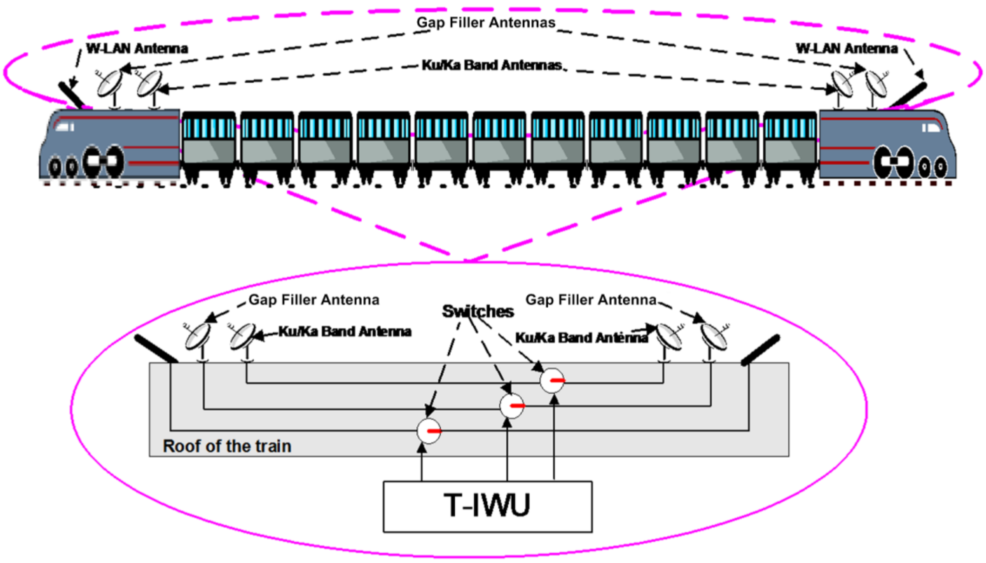

Figure 4-4: Train Implemented with Antenna Diversity

Handover in train station

For handover in a train station environment with the gap filler implemented by means of W-LAN (see Figure 4-5), the handover procedure is similar to that executed in the tunnel implementing W-LAN. The same requirements discussed before may be repeated (in particular no impact at network layer is caused). The utilisation of location detection procedures and antenna diversity could be applied for handover as stated above.

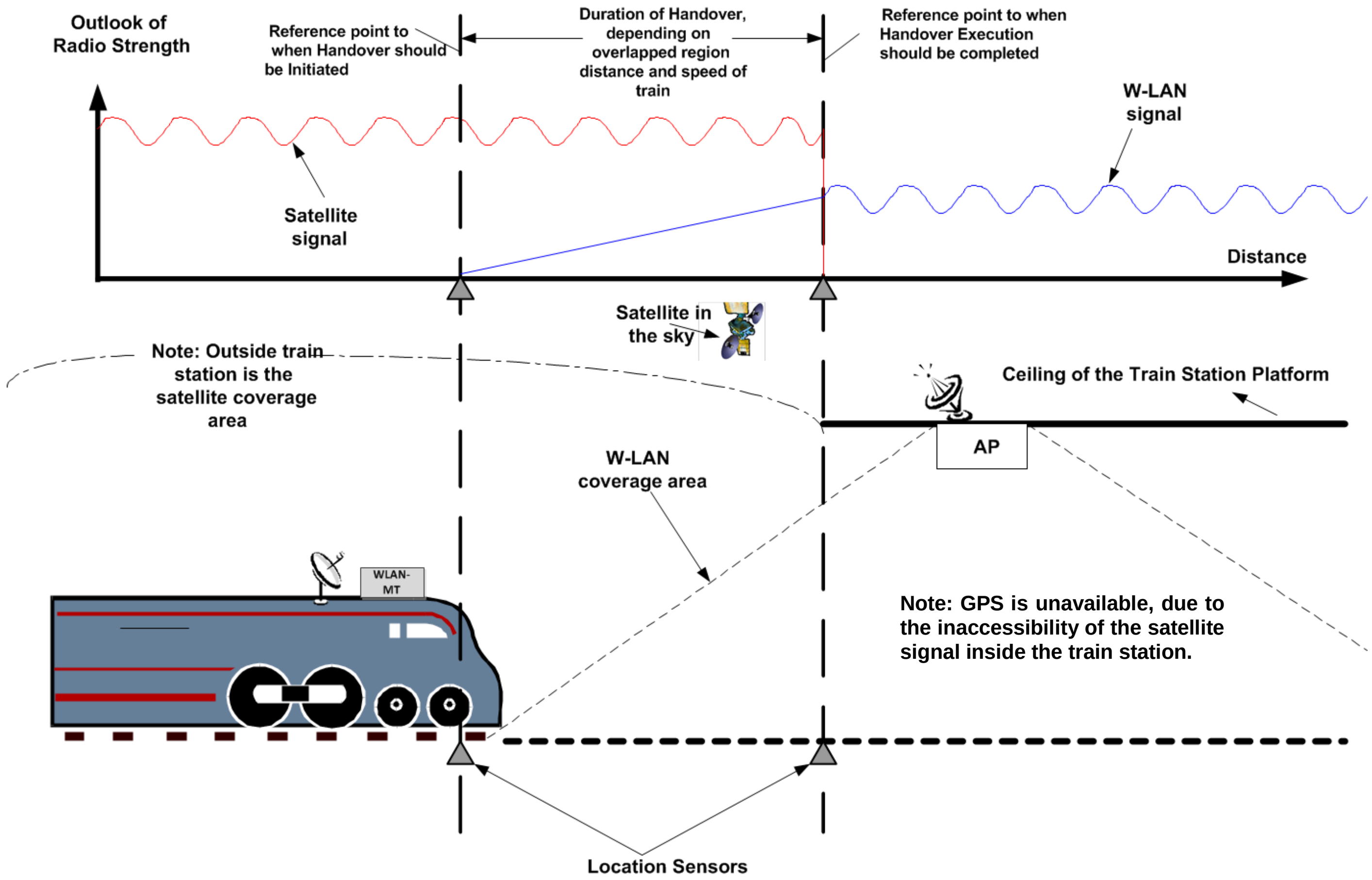

Figure 4-5: Inter-Segment Handover Scenario for Train Station in a single-segment access network

4.4 Design Decisions

4.4.1 Proposed Handover Strategies Approach

It was stated that a handover consist of three procedures and the proposed approach is as follows:

- **Handover Controlling Scheme**

  Mobile Controlled Handover (MCHO): This scheme, which was discussed in Section 3.2.2.2, is suitable for fast handover and in a fast train environment where the speed of the train could be up to 300 km/h, it is necessary for the handover to be as quick as possible.

- **Connection Establishing Scheme**

  Forward Handover: This scheme was discussed in Section 3.2.2.3. With the train travelling at very high speed, the establishment of the new channel in the extended segment should be completed before the MT leaves the coverage area of the old channel.

- **Connection Transference Scheme**

  Signalling Diversity: This scheme, refer to Section 3.2.2.4, requires no synchronisation between the two connections because the signalling exchange is done in the targeted connection and the traffic link would be the current link. Moreover, the propagation delay difference would be reduced to the handover duration between the satellite and the extended segment. This would be ideal for a fast train environment whereby a fast handover is required and is illustrated in Figure 4-6.

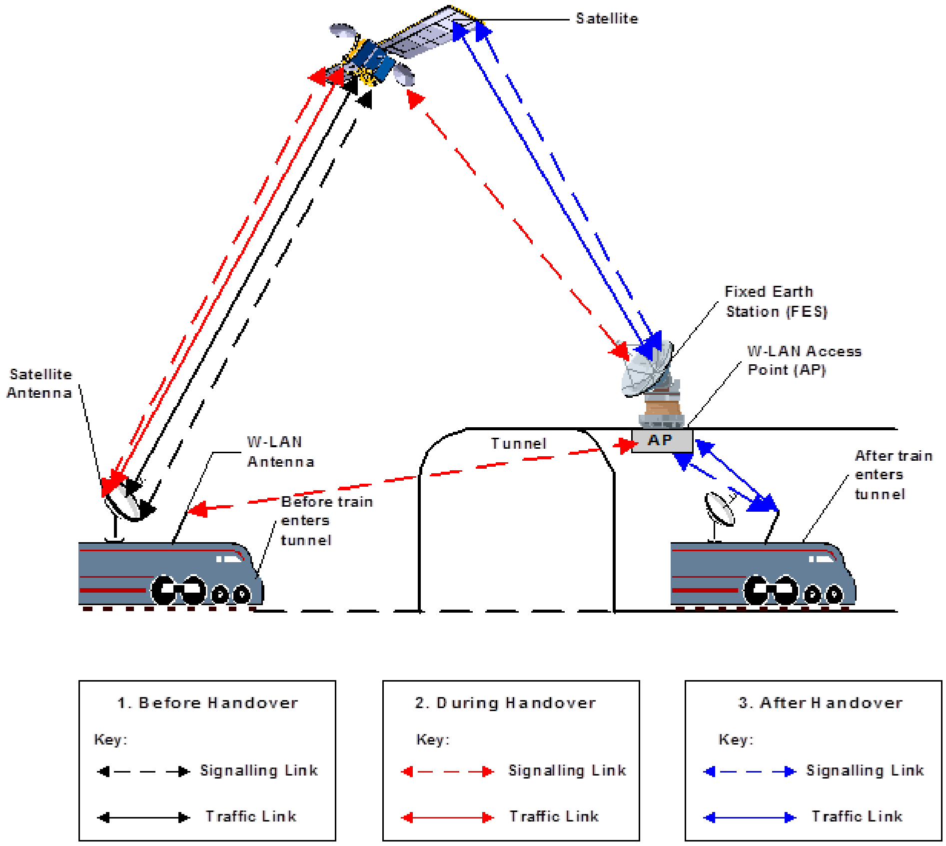

Figure 4-6: Signalling Diversity Scheme

4.4.2 Functional Models Approach

The approach adopted for the functional models are based on the RACE II MONET [83] and ITU-T Q.65 design methodology [84]. The MONET methodology allows a systematic procedure to integrate user requirements into a real system. This technique has successfully been adopted in the SINUS [85] and SUITED [72] projects for mobility management procedures and is deemed appropriate for the design of the handover functional model in this research study. The ITU-T Q.65 methodology was also adopted in the design of the functional entities and information flows for the functional model. The functional model is then mapped onto the ITU-T Q.1711 IMT-2000 functional architecture [86].

4.5 Functional Design for Inter-Segment Handover Management

4.5.1 Overview

As mentioned in Section 4.4.2, the handover management procedures are based on the MONET and ITU-T Q.65 design methodology. The handover FM is first identified and from this, the FUA is derived to assist the derivation and implementation of the signalling protocols. The FUA is based on the Q.1711 IMT-2000 FM, which is used as a reference in the FUA. A brief summary of the methodologies adopted in the design approach will be presented in this section, which will aid in understanding the remainder of Section 4.5.

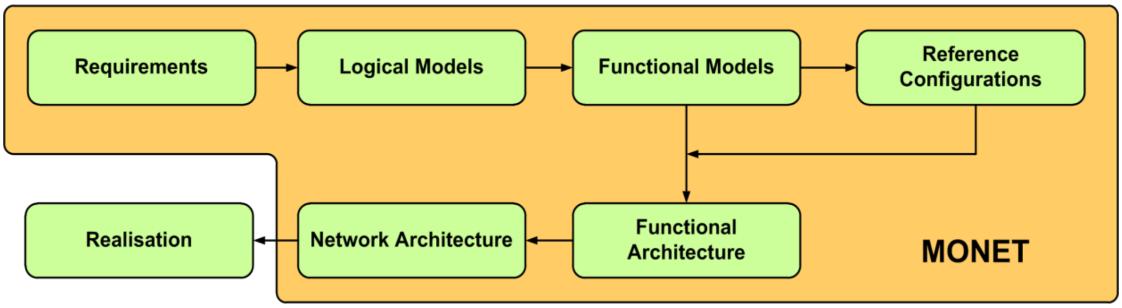

Figure 4-7: MONET Design Methodology

<u>Monet Design Methodology</u>

The MONET design methodology in brief takes into consideration the “user’s need” as input and, based on the input, identifies the operational and functional requirements of the system. This approach is based on the ITU Recommendation I.I30 [87] and the Intelligent Network (IN) Conceptual Model [88]. The procedure of the methodology is shown in Figure 4-7.

Unified Functional Model

The Unified Functional Model (UFM), defined in [84], is an approach based on the practical usage of ISDN stage 2 methodology , IN methodology and distributed computing techniques derived from Rumbaugh, Booch *et al* [89] and refined using unified modelling language (UML) [90, 91]. This approach, which consists of six steps, allows the functional descriptions of services, such as INF and Functional Entity (FE) actions. The six steps are shown in Table 4-1. In this research, step 3, which identifies and defines the INFs, was adopted in the handover design. An interaction that occurs between two FEs is known as an *information flow*.

Steps	Application of Method
1	Functional Model
2	Service Independent Building Blocks (SIB) Description of Service Features
3	Information Flow Diagrams
4	Functional Entity Actions
5	System Description and Specification Language (SDL) Diagrams for FEs
6	Allocation of FEs to Physical Locations

Table 4-1: Steps in Unified Functional Model

Functional Model

The FM comprises two components, namely FEs and INFs. The FEs are symbolised by a circle and a connecting line between two FEs indicates the communication between them. Within the FM, all sets of INFs between the FEs and the message format are specified. The message formats can be found in Appendix B.

A FE is a grouping of service providing functions in a single spatial location that cannot be split anymore when mapped onto a physical entity (PE).

Moreover, a FE is a subset of the total set of functionalities required to provide the service. The FE is “service specific”, which implies that the FM is custom built for a particular kind of service to be implemented by a service provider.

Functional Architecture

The FUA consists of the Network Entities (NEs) and the Functional Interfaces (FIs). The FUA serves as the development and specification of application layer protocols without the need to take into consideration the lower layer protocol layers that provide a reliable communication channel between the application processes.

A NE is a grouping of FEs belonging to the same spatial area, and it can be mapped onto a single piece of equipment. The NE is not allowed to exist in more than a single piece of equipment but multiple NEs can be mapped onto one piece of equipment for implementation.

When a relationship already exists between a pair of FEs in the FM, and if the FEs are mapped onto different NEs, then a FI is required to reflect this link between the two NEs. The INFs between FEs mapped onto different NEs must be translated into Application Layer Protocols; IFs between FEs mapped in the same NE do not determine the development of a FI.

Network Architecture

The network architecture (NA) comprises of several PEs which depicts the physical behaviour of the system. The FEs, defined in the FM, are mapped onto the PEs, which could correspond to a single physical location or equipment. The interactions between the PEs are defined by the physical interfaces (PIs).

4.5.2 Functional Model

The FM consists of three phases: information gathering phase; decision phase; and execution phase. The FEs involved in each phase will be discussed in this section. The adopted handover controlling scheme, as discussed in Section 4.4.1, is MCHO, which implies that the MT is in control.

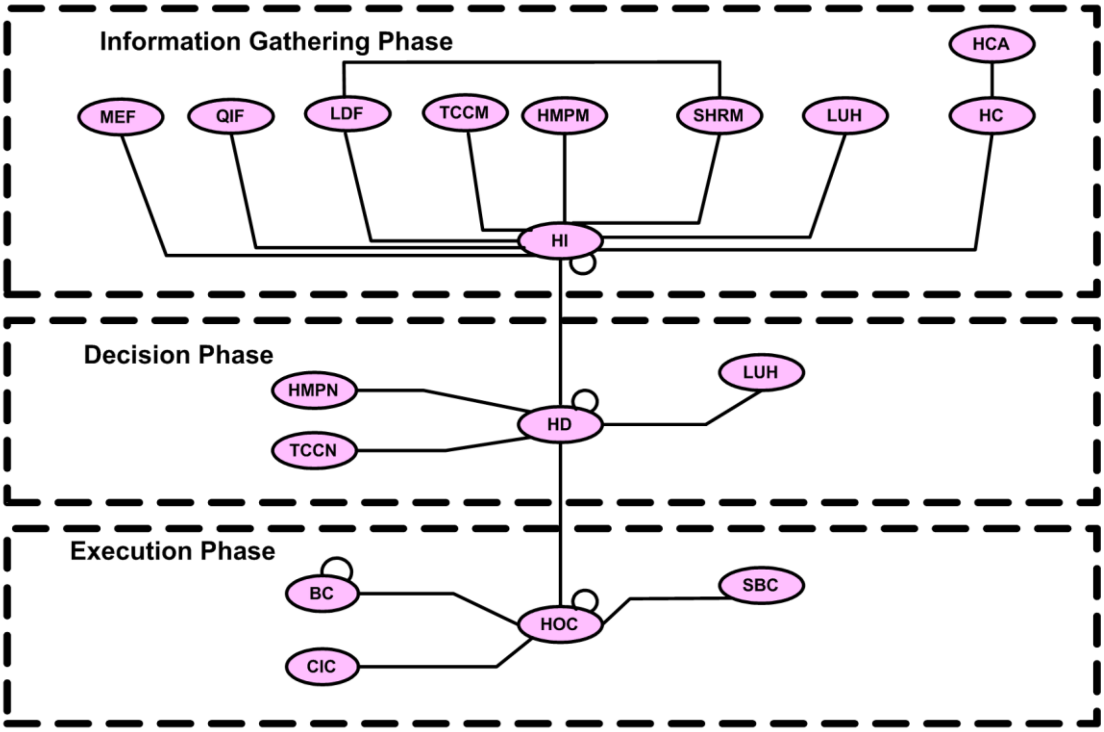

Figure 4-8: ISHO Functional Model

<u>Information Gathering Phase</u>

The information gathering phase consists of 18 FEs, as shown in Figure 4-8, and the functionality of each FE are described below.

- Measurement Function (MEF)

This FE measures the parameters of the active link needed for the handover initiation process. The parameters include the Bit Error Rate (BER), delay, delay jitter, the signal strength, etc. Depending on the current active link, either the satellite or W-LAN or gap fillers, the set of evaluated parameters may vary. These parameters define the quality of the link and are forwarded to HI on a regular basis.

- Quality Information Function (QIF)

This FE provides the current active link's overall QoS information perceived by the MT. This information is then regularly forwarded to the HI. For example, if the MT is currently using the satellite link, the FE should forward the satellite's overall QoS information perceived by the MT to the HI.

- Location Detection Function (LDF)

This FE forwards the current geographic positioning of the MT to the HI. The geographic positioning could be determined either by Global Positioning System (GPS) or location sensors.

- Target Cells and Connection – MT (TCCM)

This FE provides a set of candidate cells for each access segment to the HI. It should also provide information regarding the targeted access segment, such as the radio link quality, the available bandwidth, the cell capacity vs. cell population, etc. The HI should then be able to evaluate the QoS of the targeted segment.

- Handover Mobile Terminal Profile – MT (HMPM)

This FE contains a subset of the MT profile, specifically all information related to the handover process. The information is such as the QoS requirement, bandwidth requirement, priority list, access rights etc. HI processes this information.

- Special Handover Request – MT (SHRM)

This FE determines when a handover should be initiated based on the location information provided by LDF. SHRM evaluates the current geographic position of the MT and determines if the MT is at the allocated point of the journey whereby a handover should be initiated. If a handover initiation is required, SHRM then sends a forced handover request to HI. The request is based on the location information and should be initiated by the MT.

- Handover Criteria (HC)

During handover, this FE provides the handover criteria for HI. It can be changed according to the current active link and the threshold for the criteria is based on the information provided by MEF and the current location of the MT.

- Handover Criteria Adjustment (HCA)

This FE updates the handover criteria FE, based on the instructions received from the resource control and the network management.

- Location Update Handler (LUH)

The FE provides the latest update of the available access segment that is discussed and elaborated in location management. For the handover process, the database report is forwarded to HI.

Decision Phase

- Handover Initiation (HI)

This FE is located at the MT, because the handover controlling scheme used is MCHO. This FE processes the information provided by MEF, QIF, LDF, TCCM, HMPM, HC, SHRM and LUH. The criteria for handover initiation should first be fulfilled. The HI achieves this by evaluating the measurements and the location positioning information, provided by MEF and LDF respectively, with the threshold supplied by HC. HI then corresponds with HMPM to identify the need for a handover. It also communicates with TCCM to determine the available targeted cell /s. The HI also receives requests from SHRM to initiate a forced handover, based on information provided by LDF and, upon completion of the forced handover, HI would respond to SHRM.

If a handover is required, a handover execution request is then issued to HD. Information relevant for identifying the new handover control point is also forwarded to HD. This is because for the handover execution, HD requires information regarding the type of handover, time constraints, QoS, etc.

- Handover Mobile Terminal Profile – Network (HMPN)

This FE contains a subset of the MT and the service profile, such as the bandwidth and QoS requirements. This implies that handover initiated was executed and based on the information provided; HD uses it for service degradation negotiations provided to the MT.

- Target Cell and Connection – Network (TCCN)

This FE provides information of the available resources in the targeted segments to HD. HD uses this information for negotiations on the service degradation provided to the MT.

- Handover Decision (HD)

This FE receives the handover execution request from HI and processes it. It uses information provided by TCCN and HMPN to negotiate service degradation and also to decide on the target segment. With the information provided by HI, HD then corresponds with TCCN regarding the QoS availability in the target segment. It then checks with the QoS requirements provided by the network. If HD decides to execute a handover, a handover execution command, including the handover completion time constraint, is then issued to HOC. Upon which, HD would notify HI of the HD phase result.

- Location Update Handler (LUH)

This was elaborated in location management but for handover, this FE is updated with the result of the target segment.

Execution Phase

- Handover Execution Control (HOC)

This FE receives the handover execution command from HD and the handover completion time constraint information. HOC is also responsible for co-ordinating all the functional entities involved in the handover process such as BC, CIC and SBC. Upon completion of the handover execution phase, HOC notifies HD of the result of the process.

- Bearer Control (BC)

This FE receives information from HOC to establish or release bearers in the new segment. The result of this process is then passed on to HOC.

- Confidentiality and Integrity Control (CIC)

This FE was derived from [92] and is in charge of providing synchronisation of the encryption devices during the information exchange process. It also upholds the needed level of security as requested by HOC.

- Switching and Bridging Control (SBC)

This FE is responsible for the bridging and switching functions. That is, it switches from one bearer to another, and can also release and establish a bridge among several bearers. It receives its instruction from HOC and notifies HOC of the result of the process.

4.5.3 Information Flows

4.5.3.1 Introduction

The INF reflects the interaction that occurs between FEs. The adopted approach is based on [84] and the following guidelines are taken into consideration when defining the INFs.

- Receipt and emission of user inputs/outputs and INF are shown by horizontal lines across the relevant FE columns. Conversely, the absence of a line indicates no receipt or emission.
- INFs are depicted by arrows with the name of the INF above and below the arrow. The descriptive name is written in capitals above the arrow and the label (e.g. req.ind.) is written below the line in lower case. For unconfirmed INFs and the "request" part of confirmed INFs, the label "req.ind." is shown in lower case below the INF arrows. For the "confirmation" part of confirmed INFs, the "resp.conf" is used.
- In a particular FE column:
  - Actions shown below a line representing the receipt of a user input or INF are dependent upon that receipt (i.e. they cannot be carried out beforehand).
  - Actions shown above a line representing the emission of a user output or an INF must be completed prior to the emission flow.
  - Actions shown below a line representing the emission of user output or INF do not need to be completed before emission. No constraint

on the relative order of the emission and the action which immediately follows it is intended.

- The Stage 1 service interactions are inputs and outputs from the Stage 2 INF diagram. Stage 1 service interactions from the user are either of the form YYY.req or YYY.resp. Stage 1 service interactions to the user are either of the form YYY.ind or YYY.conf.
- Numbering of FEs

  FEs are numbered ABC, where: A represents the FE number; B is the number of the FE where the action is executed; C specifies the actions in a single FE. The FE number, i.e. A, representing the respective functionality is shown in Table 4-2.

FE Number	Functionality
2	Call Control Function / Service Switching Function
3	Specialised Resource Function
4	Service Data Function
9	Service Control Function

Table 4-2: List of FE Number corresponding to functionality

4.5.3.2 Information flow for Handover Initiation

The INFs in Figure 4-9 and Figure 4-10 illustrate two types of proposed handover initiation. Figure 4-9 depicts the handover initiation INF which takes into consideration factors such as the RSS and geographic positioning of the train. Handover initiation can also be triggered solely based on the geographic positioning of the train with the aid of GPS and location sensors.

Figure 4-10 depicts the INF for handover initiation based only on the location detection procedures.

Information Flow for Handover Initiation based on several factors

The information flow for this handover initiation is illustrated in Figure 4-9. To trigger the handover initiation, factors such as the quality of the radio link, the geographic positioning of the train and QoS issues are taken into consideration. The messages exchanged between FEs are explained in Table 4-3. The FE actions (FEAs) are explained in Table 4-4.

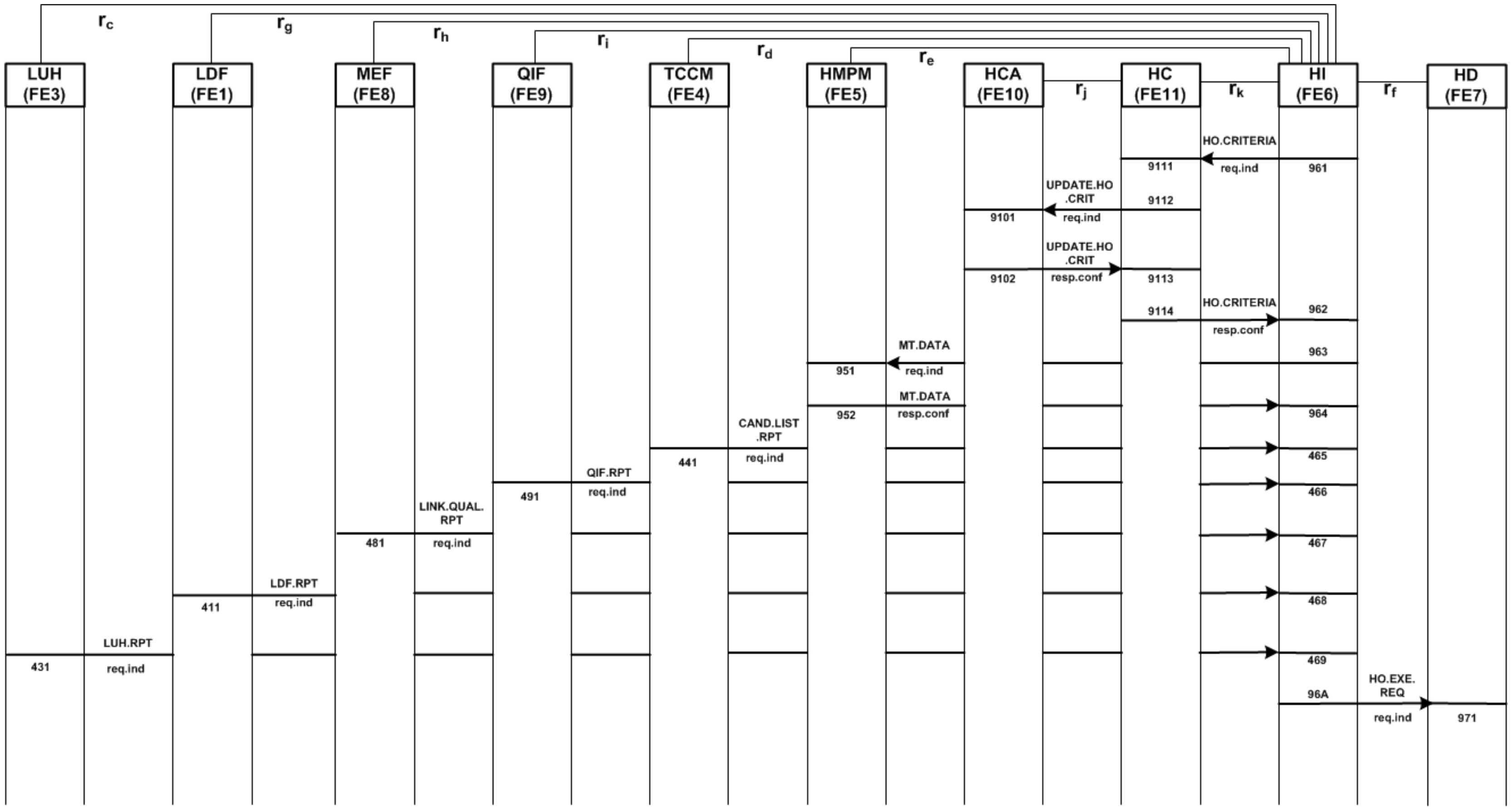

Figure 4-9: Information Flow of Handover Initiation

Messages	Message Description
HO.CRITERIAreq.ind	Requests for relevant handover criteria.
HO.CRITERIAresp.conf	Handover criteria response.
UPDATE.HO.CRITreq.ind	Requests for handover criteria update.
UPDATE.HO.CRITresp.conf	Handover criteria update response.
MT.DATAreq.ind	Requests for MT related information.
MT.DATAresp.conf	MT related information response.
CAND.LIST.RPTreq.ind	Provides HI with a list of candidate elements and is updated periodically.
QIF.RPTreq.ind	Report of the current access segment overall quality performance.
LINK.QUAL.RPTreq.ind	Report of the radio link quality and is sent periodically.
LDF.RPTreq.ind	Report of geographic positioning of train and is sent periodically.
LUH.RPTreq.ind	Report of available access segment and is sent periodically.
HO.EXE.REQreq.ind	Handover execution request and is sent to HD.

Table 4-3: Message Description of Information Flow for Figure 4-9

FE	FE No.	FEA No.	FEA Description
LUH	FE3	431	Sends available access segment report to HI.
TCCM	FE4	441	Sends a list of candidate elements to HI.
HMPM	FE5	951	Receives request from HI for MT information.
		952	Responds to HI request and sends MT information to HI.
HI	FE6	961	Requests to HC for handover criteria.
		962	Receives handover criteria information from HC.
		963	After FEA 961 and FEA 962 are completed, HI is then able to request HMPM for MT information.
		964	Receives MT information from HMPM.
		465	Receives candidate elements from TCCM.
		466	Receives report of overall quality performance of current access segment from QIF.
		467	Receives radio link quality report from MEF.
		468	Receives report on current geographic positioning of train from LDF.

		469	Receives report on current available access segments from LUH.
		96A	After FEA 961 to FEA 964 and FEA 465 to 469 are completed, HI processes the information received. If handover initiation is required, HI sends HD a handover execution request to proceed with the handover decision phase.
HD	FE7	971	Receives handover execution request from HI, which implies to proceed with the handover decision phase.
LDF	FE1	411	Sends current geographic position of MT report to HI.
MEF	FE8	481	Sends radio link quality report to HI.
QIF	FE9	491	Sends overall quality performance of current access segment report to HI.
HCA	FE10	9101	Receives handover criteria update request from HC.
		9102	Responds to handover criteria update requested by HC.
HC	FE11	9111	Receives handover criteria request from HI.
		9112	Sends handover criteria update request to HCA, so as to respond to HI.
		9113	After FEA 9111 and 9112 are completed, HC receives handover criteria update response from HCA.
		9114	After FEA 9113 is completed, HC sends handover criteria response to HI.

Table 4-4: Functional Entity Actions for Figure 4-9

Information Flow for Handover Initiation based only on Location Detection

As mentioned previously, handover initiation can be triggered based only on location detection information with the aid of GPS or location sensors. The information flow for this type of handover initiation is illustrated in Figure 4-10. LDF provides SHRM with the geographic positioning of the train, which SHRM evaluates to determine if it is the pre-determined point whereby handover should be initiated, upon which, SHRM will send a request to HI to initiate a forced handover. The explanation for the messages exchanged is provided in Table 4-5. Table 4-6 describes the FEA in Figure 4-10.

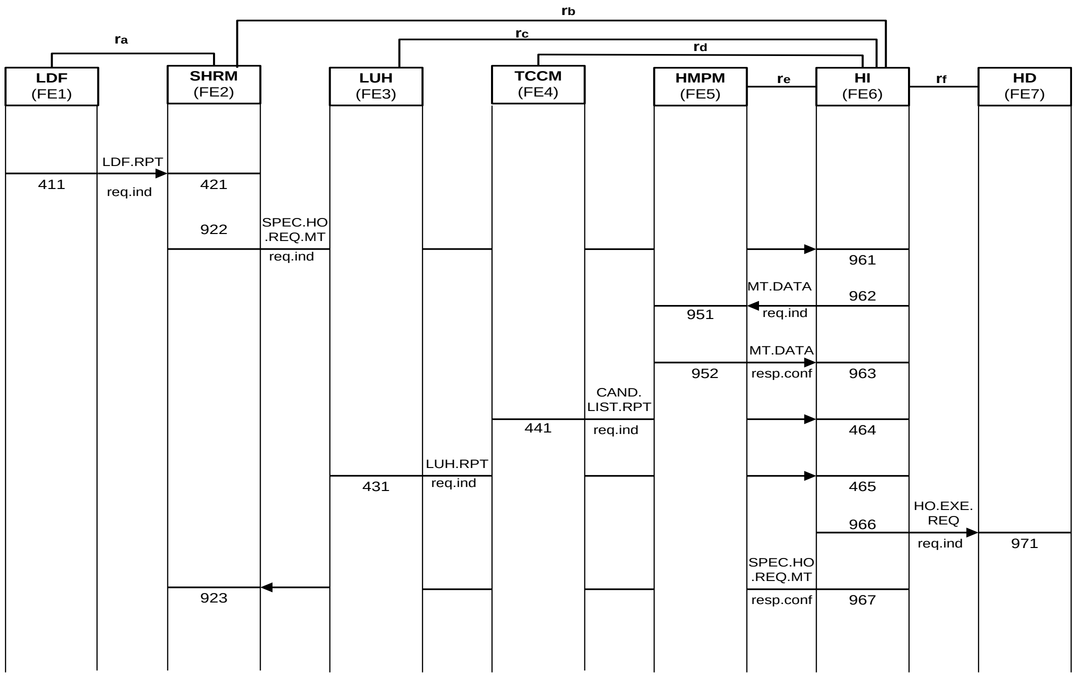

Figure 4-10: Information Flow of HI based on Location Detection

Messages	Message Description
LDF.RPTreq.ind	Reports of geographic positioning of train and is sent periodically.
SPEC.HO.REQ.MTreq.ind	Evaluates LDF.RPTreq.ind and when required sends a forced handover initiation request to HI.
SPEC.HO.REQ.MTresp.conf	Response to the forced handover initiation request.
MT.DATAreq.ind	Requests for MT related information.
MT.DATAresp.conf	MT related information response.
CAND.LIST.RPTreq.ind	Provides HI with a list of candidate elements and is updated periodically.
LUH.RPTreq.ind	Report of available access segments and is sent periodically.
HO.EXE.REQreq.ind	Handover execution request and is sent to HD.

Table 4-5: Message Description of Information Flow for Figure 4-9

FE	FE No.	FEA No.	FEA Description
LDF	FE1	411	Sends current geographic position of MT report to HI.
SHRM	FE2	421	Receives report on current geographic positioning of train from LDF and evaluates if handover initiation is required based on the report.
		922	If handover initiation is required, SHRM sends a forced handover request to HI.
		923	After the completion of FEA 921 and FEA 922, SHRM receives a forced handover response from HI.
LUH	FE3	431	Sends available access segment report to HI.

TCCM	FE4	441	Sends a list of candidate elements to HI.
HMPM	FE5	951	Receives request from HI for MT information.
		952	Responds to HI request and sends MT information to HI.
HI	FE6	961	Receives forced handover request from SHRM to initiate handover.
		962	After FEA 961 is completed, HI is then able to request HMPM for MT information.
		963	Receives MT information from HMPM.
		464	Receives candidate elements from TCCM.
		465	Receives report on current available access segments from LUH.
		966	After FEA 961 to FEA 965 are performed, HI processes the information received. As it is a forced handover, HI sends HD a handover execution request to proceed with the handover decision phase.
		967	After the completion of FEA 961 to FEA 966, HI sends a response to SHRM.
HD	FE7	971	Receives handover execution request from HI, implying to proceed with the handover decision phase.

Table 4-6: Functional Entity Actions for Figure 4-10

4.5.3.3 Information flow for Handover Decision

In the information gathering phase, HI analyses the factors and initiates a handover by sending a handover execution request to HD. The information flow for the decision phase is shown in Figure 4-11. The explanation of the messages exchanged between FEs is shown in Table 4-7. The FEA is explained in Table 4-8.

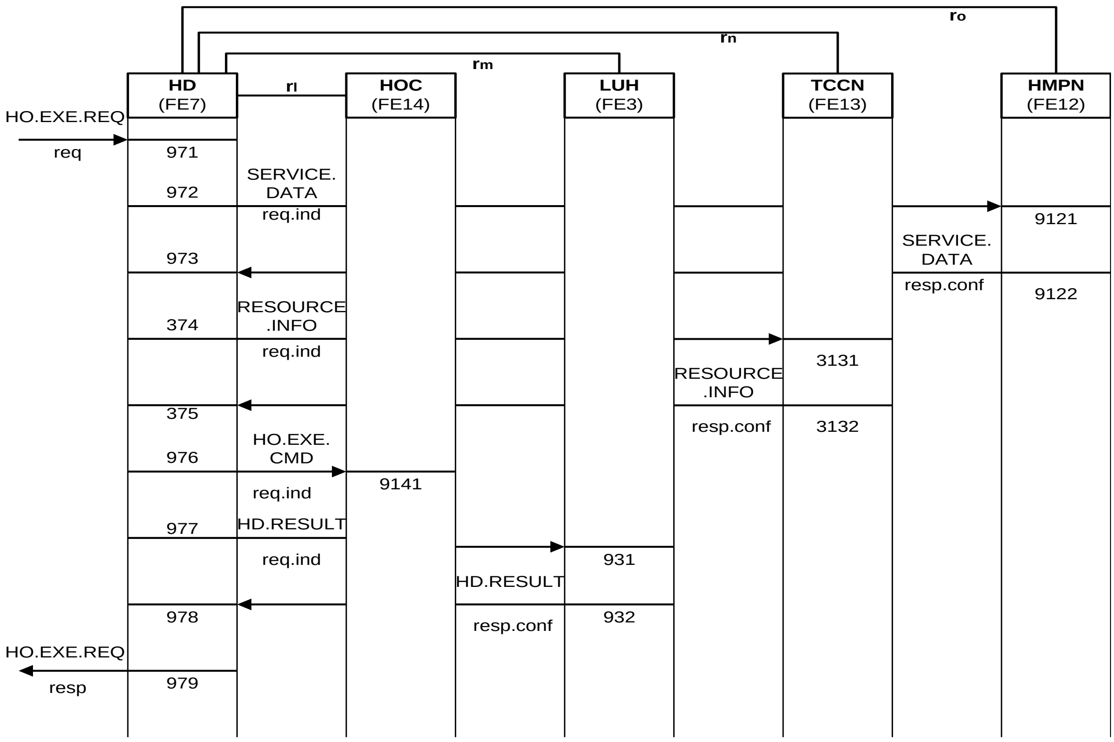

Figure 4-11: Information Flow of Handover Decision

Messages	Message Description
HO.EXE.REQreq	If handover initiation is required, HI sends HD a handover execution request to proceed with the handover decision phase.
HO.EXE.REQresp	Response to the handover execution request.
SERVICE.DATAreq.ind	Request for service related information.
SERVICE.DATAresp.conf	Response to service related request.
RESOURCE.INFOreq.ind	Request for information regarding the available resources in the targeted segment.
RESOURCE.INFOresp.conf	Response to resource information request.
HO.EXE.CMDreq.ind	Handover execution command to initiate handover control function.

HD.RESULTreq.ind	Notification of the handover decision result.
HD.RESULTresp.conf	Response to the notification of the handover decision result.

Table 4-7: Message Description of Information Flow for Handover Decision

FE	FE No.	FEA No.	FEA Description
LUH	FE3	931	LUH receives the notification from HD and updates its database about the result of the handover decision.
		932	Sends a response to HD.
HD	FE7	971	Receives a handover execution request from HI, implying to proceed with the handover decision phase.
		972	Upon receiving the handover execution request from HI, HD sends a service data request to HMPN.
		973	After completion of FEA 972, it receives a response from HMPN regarding its request.
		374	After the completion of FEA 973, HD requests for information about the resource availability from TCCN.
		375	Receives a response about resource availability from TCCN.
		976	After the completion of FEA 971 to FEA 976, HD processes the information and sends a handover execution command request to HOC.
		977	Sends a report to update LUH about the result of the handover decision.
		978	Receives a response from LUH.

		979	Notifies HI about the result of the handover decision.
HMPN	FE12	9121	Receives request for service related information from HD.
		9122	Responds to HD request and sends service related information.
TCCN	FE13	3131	Receives request for resource availability information of targeted segment from HD.
		3132	Responds to HD request and sends resource availability information of targeted segment.
HOC	FE14	9141	Receives the handover execution command request from HD to proceed with the execution phase.

Table 4-8: Functional Entity Actions Description for Handover Decision

4.5.3.4 Information flow for Handover Execution

The HE and the information flow for HE is illustrated in Figure 4-12 and Figure 4-13 respectively. Figure 4-12 shows the information flow for handover execution from the old segment to the new segment. Figure 4-13 depicts the switching between bearer connections, as antenna diversity was previously discussed. SBC FE is the switching between two antennas that is connected to the same radio link.

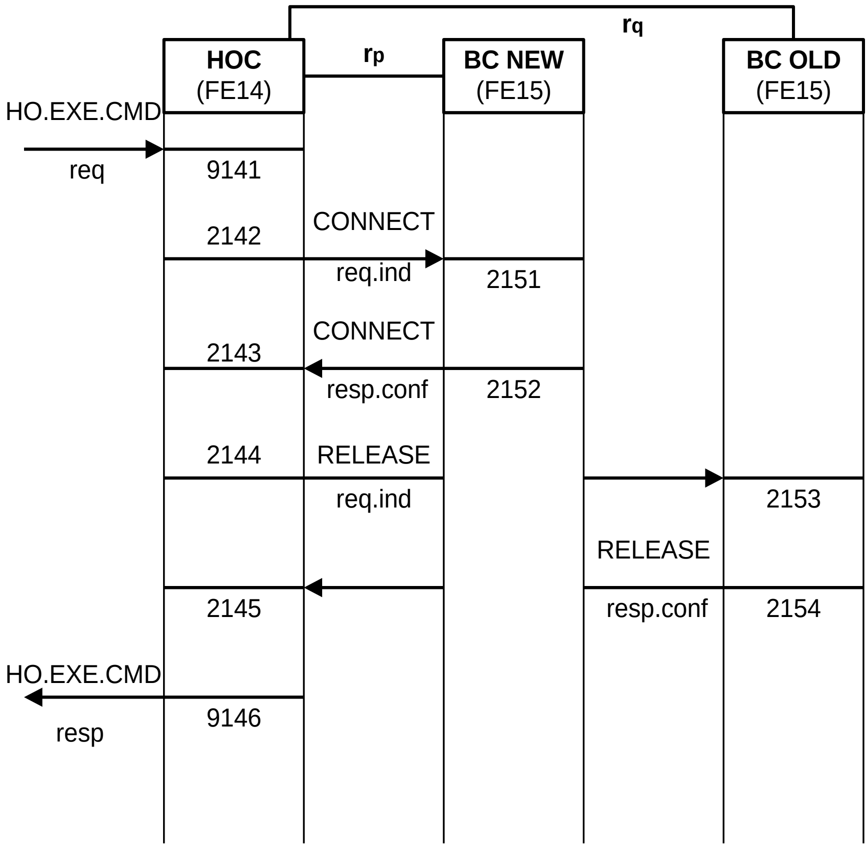

Figure 4-12: Information Flow for Handover Execution

The messages exchanged between the FEs for Figure 4-12 are explained in Table 4-9 and the FEAs are described in Table 4-10.

Messages	Message Description
HO.EXE.CMDreq	HD sends a handover execution command to initiate the handover control function.
HO.EXE.CMDresp	Notification to HD about the result of the handover process.
CONNECTreq.ind	Request for a new connection to the targeted segment.
CONNECTresp.conf	Reporting if the connection to the targeted segment is established.
RELEASEreq.ind	Request for release of the old segment connection.
RELEASEresp.conf	Reporting if the old connection has been released.

Table 4-9: Message Description of Information Flow for Handover Execution

FE	FE No.	FEA No.	FEA Description
HOC	FE14	9141	Receives the handover execution command from HD, to proceed with the handover control function.
		2142	HOC sends a request to BC new to request for connection to the targeted segment.
		2143	Upon completion of FEA 2142, HOC receives a notification of whether the connection has been established.
		2144	When FEA 2143 is completed, HOC sends a request to BC old to release the old connection.
		2145	When FEA 2144 is completed, HOC receives a notification from BC old about the result of the request.
		9146	HOC then notifies HD about the result of the handover process.
BC NEW/ OLD	FE15	2151	Receives connection establishment request from HOC.
		2152	Responds to HOC about the result of the connection establishment request.
		2153	Receives release connection request from HOC.
		2154	Notifies HOC about the outcome of the release connection request.

Table 4-10: Functional Entity Actions Description for Handover Execution

For antenna diversity, the HE is between two connections that are both established on the same radio link, as shown in Figure 4-13. The messages exchanged between HOC and SBC are explained in Table 4-11. The FEAs are described in Table 4-12.

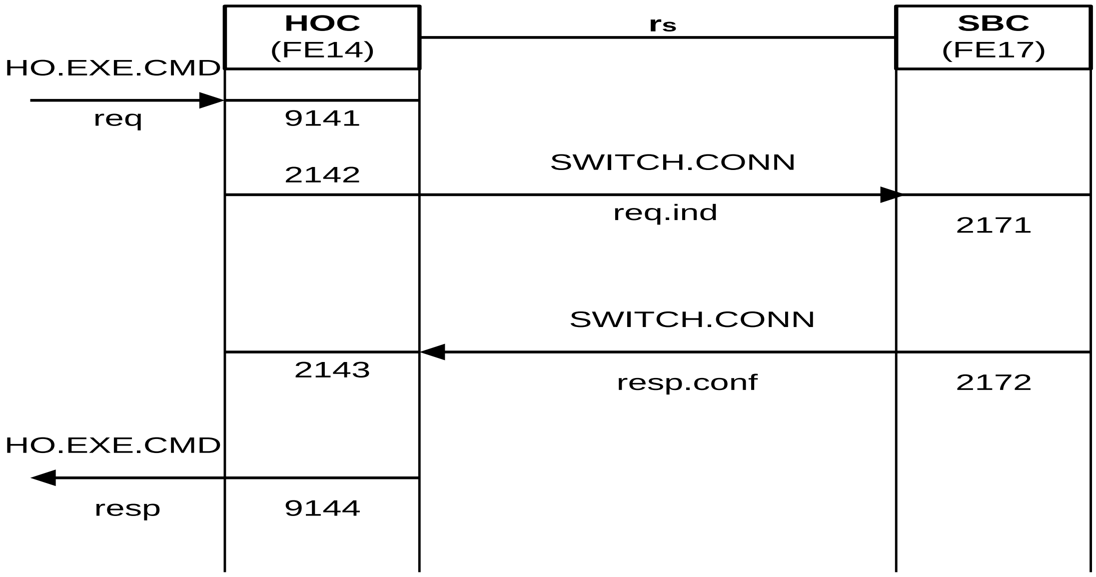

Figure 4-13: Information Flow for Switching Bearer Connection (SBC)

Messages	Message Description
HO.EXE.CMDreq	HD sends a handover execution command to initiate the handover control function.
HO.EXE.CMDresp	Notification to HD about the result of the handover process.
SWITCH.CONNreq.ind	Request to switch from one connection to another.
SWITCH.CONNresp.conf	Reporting the result of the switching request.

Table 4-11: Message Description of Information Flow for SBC

FE	FE No.	FEA No.	FEA Description
HOC	FE14	9141	Receives the handover execution command from HD, to proceed with the handover control function.

		2142	Upon receiving the handover execution command, HOC sends a request to SBC to switch to another connection.
		2143	When FEA 9141 and FEA 2142 are completed, HOC receives the outcome of the switching request from SBC.
		9144	HOC then notifies HD about the result of the handover process.
SBC	FE17	2171	Receives switching to another connection request from HOC.
		2172	Responds to HOC about the outcome of the switching request.

Table 4-12: Functional Entity Actions Description for SBC

4.6 Functional Architecture

The FEs developed and defined for the handover management in Section 4.5.2 are mapped onto the ITU-T Q.1711 functional model. There are two alternatives in the IMT-2000 functional model, as stated in [86], but only *Alternative 1* is considered here. The differences between *Alternative 1* and *Alternative 2* do not affect the mapping of FEs.

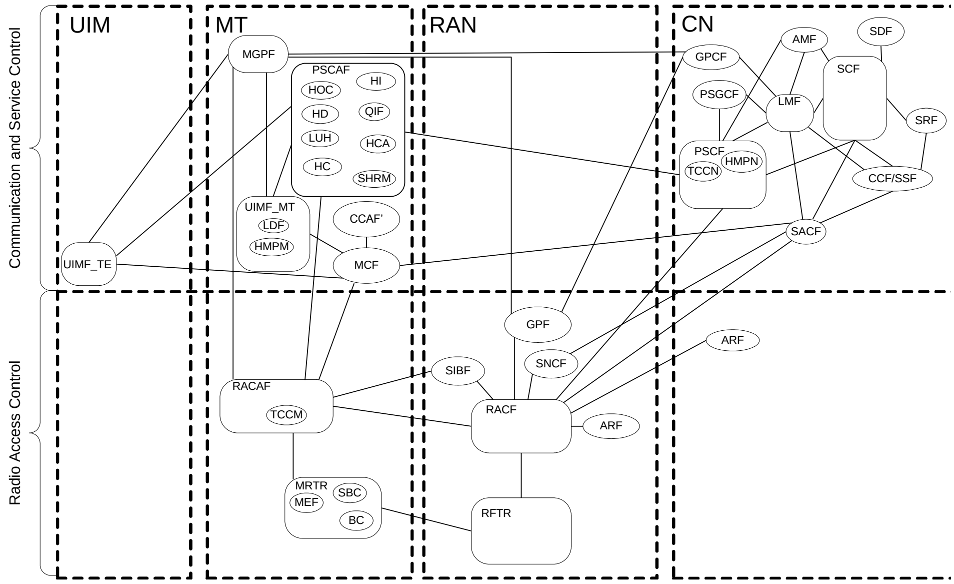

Figure 4-14: Mapping of handover FEs based on IMT-2000 FM

In Figure 4-14, a UIMF_MT FE is included for the MT. It is similar to the User Identification Management Function (UIMF) FE in the IMT-2000 functional model and is required for identification of the MT to the network and/or the service provider [86]. For handover where the location information is required, Mobile Geographic Position Function (MGPF) presents the location information of the MT to UIMF_MT. This is elaborated in [86]. Table 4-13 shows the mapping of the FEs onto the FEs of the IMT-2000 functional model. The mapping of the FEs to the baseline NA can be found in Figure 4-15.

ITU-T Q.1711 FEs	Handover FEs
UIMF_MT	HMPM, LDF
PSCAF	HOC, HI, HD, QIF, LUH, HCA, HC, SHRM
RACAF	TCCM
MRTR	MEF, SBC, BC
PSCF	TCCN, HMPN

Table 4-13: Mapping of handover FEs to ITU-T Q.1711 FEs

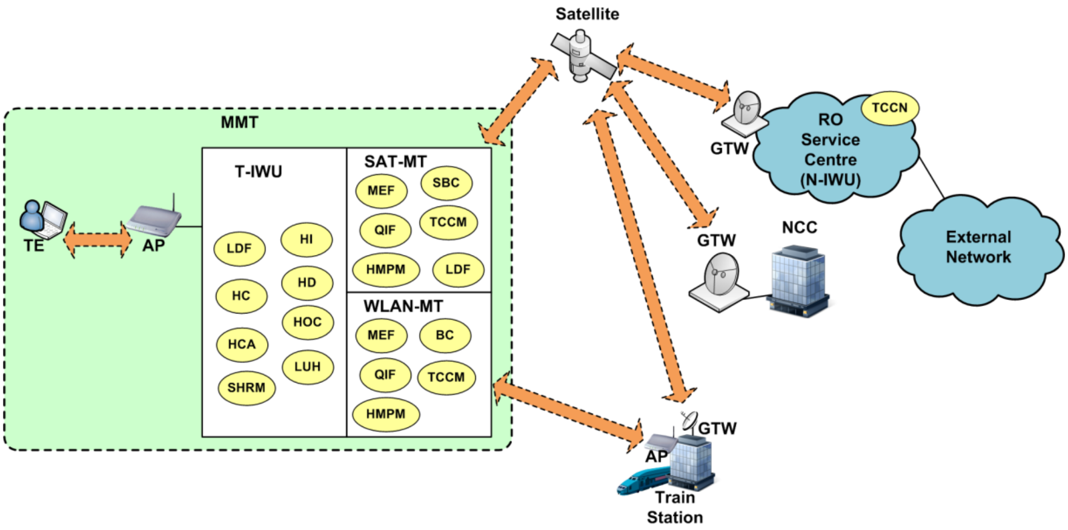

Figure 4-15: Mapping of Handover FEs onto NA

4.7 Summary

In this chapter, descriptions of the FEs from the FM were specified. The INF that defined the messages that are exchanged between the FEs were also defined. The FEs were then mapped onto the ITU-T Q.1711 functional model, which are then mapped onto the NA. This will be applied to the OPNET simulation activities that will be addressed in Chapter 6.

5 HANDOVER DECISION ALGORITHM

5.1 Scope

In traditional HO approaches, the HD outcome is largely determined by employing a heuristic approach through computation of the RSS of the system. However, it is noted in [21] that, such approach cannot be accurate and timely concurrently. This is also further corroborated in [73]. If additional HD parameters were introduced in traditional HO, it is likely that there will be a further impact on the accuracy and delay performance of the system. In a rail environment, based on the specifications in [27] and [28], it can be seen that there are benchmark performances for the accuracy and delay in handover, see section 2.2.1, and employing a traditional HD approach would most likely not be ideal.

Due to the daily route of a train's journey remaining largely unchanging, there is a logical rationale to explore if recurring patterns in the handover process can be identified. It is expected that the patterns, based on the HO parameters, will initially need to be established before applying the patterns to the HD process. Therefore, in this research study, a proposed HD algorithm based on pattern classification will be addressed and will take into account the accuracy benchmark of 99.5% in the GSM-R system for handover, which was discussed in section 2.2.1.

There are different techniques for pattern classification, also known as pattern recognition, such as template matching, statistical, structural, neural networks, and are described in [93]. It is widely known that PCNN provides efficient performance due to the prowess of handling parallel computation and also the capability to learn complex nonlinear input-output relationships, use sequential training procedures, and adapt themselves to the data [93]. This generalisation and learning behaviour displayed by the PCNN, shows the potential of employing it as an algorithm for handover decision in a rail environment. Moreover, the capability of PCNN to compute several HO parameters concurrently and the possibility of achieving a high accuracy in HO makes it an ideal candidate for adoption in a rail environment. Therefore, in this research study, the pattern classification NN (PCNN) is the preferred approach to be investigated as the HD algorithm.

In this chapter, a background into NNs will initially be addressed in section 5.2, covering the concept of perceptrons and the delta rule, which are the building blocks to comprehend how modern day neural networks work. This will also include a brief description of the renowned backpropagation (BP) algorithm. Details of the adopted methodology, such as the simulation parameters, PCNN architecture, datasets will be elaborated in section 5.3. The training algorithms to be employed in the PCNN and the number of hidden nodes to be determined are discussed in Section 5.3.2. Section 5.3.3. will present the performance function and the performance plots and conclude the chapter.

5.2 Background on Neural Networks

5.2.1 Perceptrons

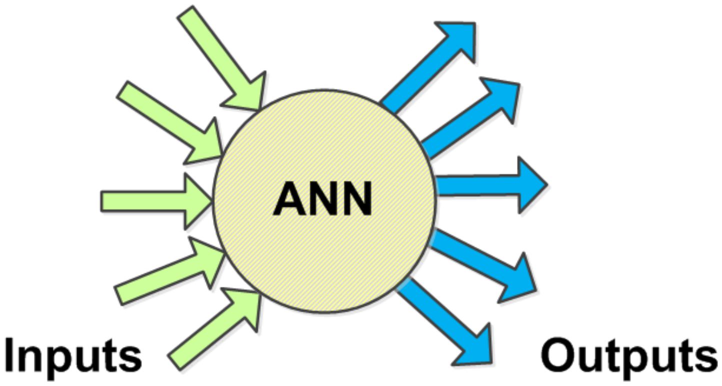

Figure 5-1: Simplified representation of ANN

The inception of artificial neural networks (ANN), also known as NN or neural nets, is inspired by the human biological nervous system (for example, the brain). It consists of inter-connected processing elements, known as neurons, which allow computation functions, such as data fitting, pattern recognition and system control, to be performed.

Based on the input information that is presented, NN are capable of producing the desired output pattern, as shown in Figure 5-1. This behaviour allows NN to be widely acknowledged as a suitable candidate for performing function approximation.

The first neural network model was developed by McCulloch and Pitts in 1943 [94]. Their work addressed the issue of integrating neurophysiology and mathematical logic. The McCulloch-Pitts model had several limitations due to its simplicity and complexity of adjusting the weights and thresholds of the model. Therefore, it was not a robust computation model and the network model was not able to learn. However, the McCulloch-Pitts model was a breakthrough in research and much development of artificial intelligence was influenced by it. Further information on the McCulloch-Pitts model is available from [94, 95].

In 1958, Frank Rosenblatt developed the perceptron based on the McCulloch-Pitts model and adopting Hebbian learning, which states [96]:

" *When an axon of cell A is near enough to excite a cell B and repeatedly or persistently takes part in firing it, some growth process or metabolic change takes place in one or both cells such that A's efficiency, as one of the cells firing B, is increased.* "

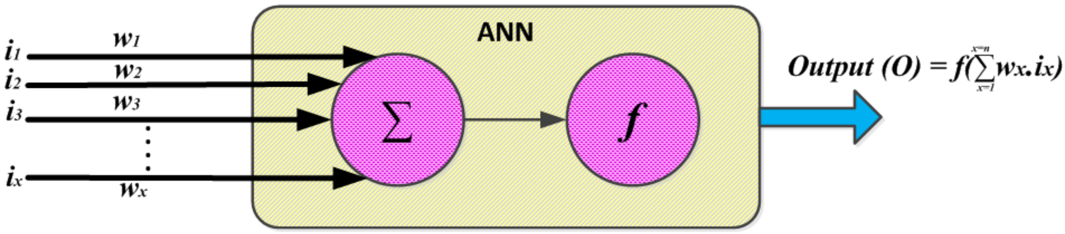

Figure 5-2: A Basic Artificial Neuron

This allowed NNs to learn by modifying the weighted inputs to improve network performance. An example of a single layer perceptron is illustrated in Figure 5-2. The following paragraphs will explain how a single layer perceptron functions, taking into account the perceptron learning and delta rule.

Figure 5-2 shows a basic artificial neuron which consists of the summed net function and the activation function (f). The artificial neuron has three inputs, i_1, i_2 and i_3, with each input associated with its respective weight, w_1, w_2 and w_3. The neuron will only be activated if the weighted sum, *net*, is above 0.5. The activation function (*f*) is threshold-based. With reference to Figure 5-2, it can be reflected mathematically as follows:

$$net = w_1 \cdot i_1 + w_2 \cdot i_2 + w_3 \cdot i_3 \qquad \text{Equation 5-1}$$

Applying the threshold function, *f(n)*, to the neuron that has the following conditions:

$$\begin{matrix} Output = 1 & net > 0.5 \\ Output = 0 & otherwise \end{matrix} \qquad \text{Equation 5-2}$$

It can be noted that if a neuron has *x* inputs:

$$net = w_1 i_1 + w_2 i_2 + w_3 i_3 + \cdots + w_x i_x \qquad \text{Equation 5-3}$$

Therefore, based on the McCulloch-Pitts algorithm:

$$net = \sum_{x=1}^{x=n} w_x i_x \qquad \text{Equation 5-4}$$

Based on Widrow-Hoff's delta learning rule, available at [97], which is a form of error-correction learning:

$$w = w_{old} + \Delta w \qquad \text{Equation 5-5}$$

where,

$$\Delta w = \eta \delta i \qquad \text{Equation 5-6}$$

The error, δ, is calculated using Equation 5-7, and η is a constant that determines the learning rate. The term, O_D, in Equation 5-7 represents the desired output of the neuron.

$$\delta = O_D - O \qquad \text{Equation 5-7}$$

The delta learning rule (DLR) is similar to Rosenblatt's perceptron learning rule (PLR) with the following main differences:

- The error (δ) in the PLR is limited to values of -1, 0 or 1, which is ideal for functions that are linear. The delta rule does not have such a restriction and is suitable for non-linear functions.

- PLR is mainly applied for threshold-based output function, whereas DLR employs differentiable activation functions, such as the sigmoid function.

The DLR is especially useful for MLP, which widely employs the log-sigmoid function, as defined in Equation 5-8. The log-sigmoid output will always be in the range between the maximum and minimum. This allows the ANN's output to gradually change between zero and one, which implies that the neuron is able to express uncertainty [98]. This is illustrated in Figure 5-3. If the output is required to be between -1 and 1, the Tan-Sigmoid activation function can be applied, which is defined in Equation 5-9. Further information and other activation functions that can be employed are elaborated in [99].

$$\boldsymbol{Output} = \frac{\mathbf{1}}{(\mathbf{1} + \boldsymbol{e}^{-\boldsymbol{net}})}$$

Equation 5-8

$$\boldsymbol{Output} = \frac{\mathbf{2}}{(\mathbf{1} + \boldsymbol{e}^{-\mathbf{2}\boldsymbol{net}})} - \mathbf{1}$$

Equation 5-9

In 1969, it was noted in [100], that a single-layered perceptron was only able to classify linear patterns and was not able to address non-linear patterns, such as the XOR function. Further research has subsequently been published, identifying the usage of MLP feed-forward ANN to address the XOR function issue. A MLP is actually a neural network that comprises an input layer, output layer and (L-1) hidden layers, whereby L represents the number of layers in the MLP. For example, a three layered MLP is shown in Figure 5-4. It consists of an input layer with three inputs, an output layer with two outputs and two hidden layers.

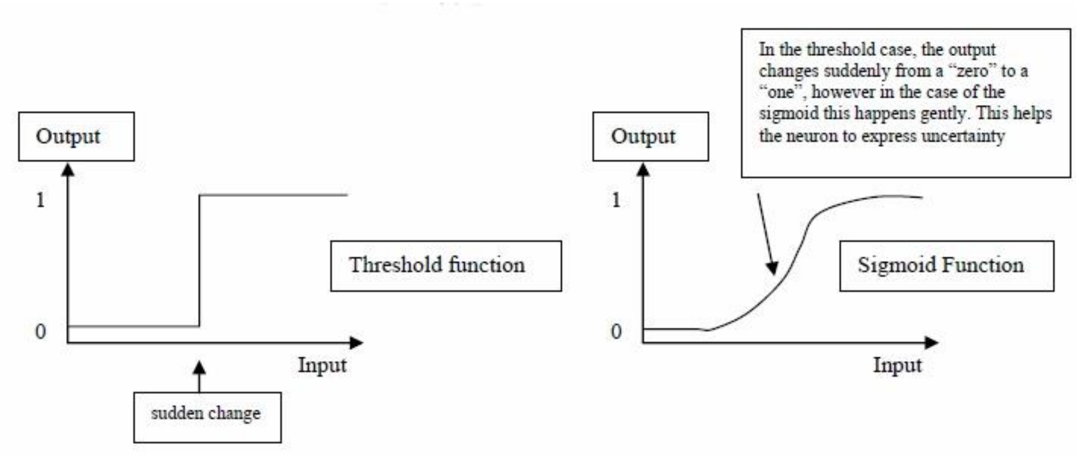

Figure 5-3: Threshold and Sigmoid Function [98]

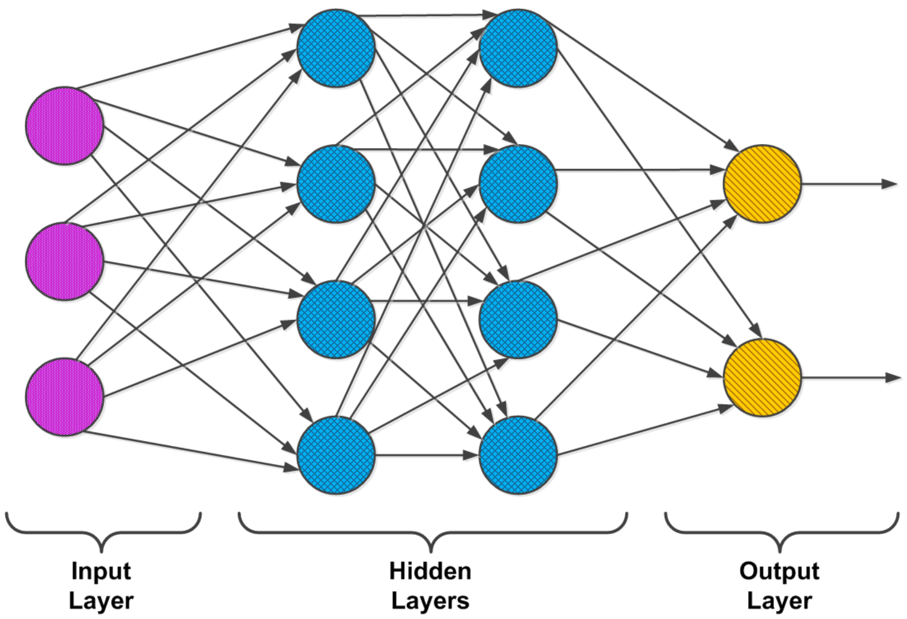

Figure 5-4: Three Layered Feed-forward MLP

5.2.2 Backpropagation (BP) Neural Networks

5.2.2.1 Overview

NN architecture can mainly be classified into two topologies, feed-forward or feed-back (also known as recurrent), as shown in Table 5-1. The BP network, which is a gradient descent technique, is an exemplary example of a MLP feed-forward network. It is basically a MLP that employs the BP learning algorithm, which is based on the DLR, to train the network. The subsequent sections will address concepts that are relevant to the BP NN. Details of other types of NN are available in [99, 101].

Artificial Neural Networks	
Feed Forward NN	Single-Layered Perceptron
	Multi-Layered Perceptron
	Radial Basis Function NN
Recurrent/Feedback NN	Competitive Networks
	Kohonen's SOM
	Hopfield Network
	Adaptive Resonance Theory models

Table 5-1: Neural Network Architecture Topologies [101]

5.2.2.2 Learning Paradigm

Training is a significant procedure in ANN, it allows the network to gather and learn from external stimuli and enhance its performance through a process called learning. A NN learns about its environment through an interactive process of adjustments applied to its weights and bias level [99]. This ability to learn makes ANN an optimum technology to be adopted in a wide variety of applications across different disciplines, such as engineering systems, neuroscience and corporate financing.

Significant research has progressed over the years concentrating on learning algorithms, which can be mainly categorised into two paradigms: supervised and unsupervised learning. Supervised learning implies that the network learns from training information, which consists of input patterns and the desired output responses. This allows the network to optimise its weights through training. Upon completion of training, the network should be able to associate the input and output information independently and also perform generalisation [102]. The term generalisation implies that when the network is presented with an unfamiliar input, it is able to map the input to comparable input information that the network was previously trained with and provide an acceptable output response. Therefore, supervised learning algorithms, such as the BP learning algorithm, are widely adopted in networks that perform function approximation and pattern classification.

For unsupervised learning, the network is only presented with input information for training and the network is then required to determine pattern classes by ascertaining similarities in the input information. Algorithms that are associated to unsupervised learning are mainly self-organising map (SOM), Dignet, learning vector quantization and adaptive resonance theory (ART). Further information on supervised and unsupervised learning algorithms can be found in [99]. Combinations of learning algorithms, known as Hybrid Learning, are possible and are employed in some NNs (such as Radial Basis Function networks). For further information of renowned learning algorithms that are used in ANN refer to [99, 101].

5.2.2.3 Backpropagation (BP) Learning Algorithm

The BP learning algorithm (BLA) is a feed-forwarded supervised learning algorithm, which implies that the network learns through provided example patterns during training. The network will also consist of at least one hidden layer. The algorithm adheres to the following procedures [101]:

1) Initial weights are set to random values. The output is then calculated based on the input value.
2) The error, δ_N, of each output neuron is then computed. If the activation function is a sigmoid, Equation 5-10 is used. If it is a threshold-based activation function then Equation 5-11 is applied.

$$\boldsymbol{\sigma_N = O_N(1 - O_N)(O_D - O_N)} \qquad \text{Equation 5-10}$$

$$\boldsymbol{\sigma_N = O_D - O_N} \qquad \text{Equation 5-11}$$

   where O_N is the output of the specific neuron and O_D is the desired output of the specific neuron.

3) The next step is to update the weight of each connection of each output neuron.

$$\boldsymbol{w_{P,N}^{new} = w_{P,N} + \eta\sigma_N O_P} \qquad \text{Equation 5-12}$$

   Therefore, $w^{new}_{P,N}$ is the new weight value for the connection between neuron, P, located in the hidden layer, and output neuron, N. $W_{P,N}$ is the current weight value, O_P is the output of neuron P in the hidden layer, and $\boldsymbol{\eta}$ is the constant learning rate, which is usually of value one.

4) The errors of each neuron in the hidden layers are then calculated by propagating the errors backwards.

$$\boldsymbol{\sigma_P = O_P(1 - O_P)\left(\left(\sigma_N \cdot w_{P,N}\right) + \left(\sigma_{(N+1)} \cdot w_{P,(N+1)}\right)\right)} \quad \text{Equation 5-13}$$

5) Similar to Step 3, the weight of each neuron in the hidden layer is then updated. These steps are for training one input pattern and will need to be repeated for subsequent patterns. This procedure goes on until: all patterns are learnt; or until the error in the output layer is below a pre-determined threshold; or a maximum number of iterations is reached [101].

Further information on BLP is elaborated in [99], [101] and [103].

The classic BP network is one of the most renowned NNs and over the years has been used in countless artificial intelligence (AI) applications. However, there are several limitations to the algorithm. One of the limitations is that BLP can get stalled at *local minima*. This is because BLP is required to adjust the weights to reduce the errors. However, in certain situations, BLP will be required to increase, in order to achieve a more general fall [98]. When *local minima* occur, the algorithm will not be able to progress and continue reducing the error. This is reflected in Figure 5-5. Another issue with the algorithm is the inadequacy of the computational speed during learning, which greatly slows down the efficiency of the network [104]. Therefore, over the years, much research development contributing to optimising the BP algorithm has been undertaken and widely published, such as, LVM, SCG, [105], and RBP [106]. The LVM technique is one of the most adopted methodologies and will be briefly addressed in the following section.

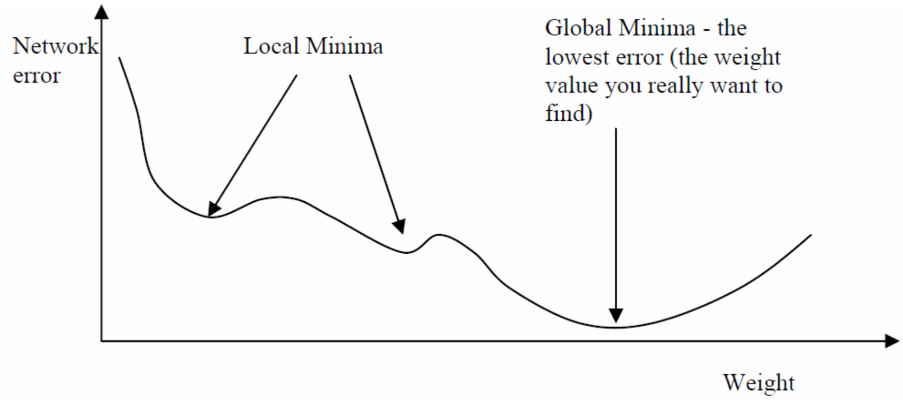

Figure 5-5: BP Network Local Minima Issue [98]

5.2.2.4 Levenberg-Marquardt Learning

The Levenberg-Marquardt (LVM) algorithm is based on the Gauss Newton methodology and was designed to approach second-order training speed without the need for computing the Hessian matrix [107]. It has been universally adopted for resolving non-linear least-squares applications and is fast for training BP NN.

Taking into consideration the error function is a certain mean squared sum, the Hessian matrix (H) is defined by Equation 5-14. The gradient is determined in Equation 5-15.

$$\boldsymbol{H} = \boldsymbol{J}^{\boldsymbol{T}} \cdot \boldsymbol{J} \quad \text{Equation 5-14}$$

$$\boldsymbol{g} = \boldsymbol{J}^{\boldsymbol{T}} \cdot \boldsymbol{e} \quad \text{Equation 5-15}$$

where *J* is the Jacobian matrix, which contains the first derivatives of the network errors with respect to the weights and biases and *e* is a vector of network errors [108]. The transpose of the Jacobian matrix is J^T, which can be determined through a standard BP technique and is significantly easier to compute than the Hessian matrix [107].

Therefore, the updated weights can be represented as follows:

$$\boldsymbol{w_{k+1}} = \boldsymbol{w_k} - (\boldsymbol{J^T} \cdot \boldsymbol{J} + \boldsymbol{\alpha I})^{-1} \cdot \boldsymbol{J^T} \cdot \boldsymbol{e} \qquad \text{Equation 5-16}$$

where *e* is the vector of network errors and *I* is the identity matrix. The parameter *α* is the damping term, which controls the behaviour of the algorithm. The algorithm moves closer to the gradient descent, when *α* is large [108]. If *α* is small or zero, the algorithm follows the Gauss Newton method closely. Further information of the derivation of the LVM algorithm is available in [109].

5.3 Adopted Methodology

5.3.1 Parameters Specification

Pattern classification NN, also known as classifiers, have been widely used in applications, such as voice-recognition, character-classification and image-recognition systems. The HD algorithm will be based on the model that is available in the MATLAB NN toolbox [110].

The training for the PCNN will employ supervised learning, which comprises training information that maps the input parameters with the expected targeted output. This training information is termed as dataset and will be assigned into matrices in MATLAB, that is, the input matrix X and the targeted output matrix Y. Hence, the main input parameters to be considered by the algorithm will need to be determined.

Informative and optional guidelines for horizontal handover performance for the GSM-R system are addressed in the system specification found in [27]. The requirements for vertical handover in a railway environment are not specified, but certain aspects of the specification can be used as a guide in the development of the HD algorithm for the satellite and WiFi scenario explored in this research study. With reference to [27], mandatory and optional services to be supported by the GSM-R system were addressed and the specification stated that QoS performance was required to be considered in the handover execution, but was not explicitly defined. Moreover, with the different services to be considered, there will also be a need to consider the supported bandwidth (BW) during handover. Therefore, the HD algorithm designed in this research study takes into consideration the following input parameters: the train's location information, RSS of the access segments, supported QoS and supported bandwidth (BW).

The train's location information will consist of the train's latitude and longitude and the chosen co-ordinates, based on the FIFTH demonstrator live trial, which assumes that a train travels from Rome (Latitude 41.89°N and Longitude 12.5°E) to Florence (Latitude 43.78°N and Longitude 11.24°E). Based on the approach in [72], normalised values of the supported QoS, BW and RSS of the access segments, namely the RSS of the satellite access segment (RSS_{sat}) and the RSS of the W-LAN access segment (RSS_{wlan}), are taken into account in the dataset. To emulate the movement of the train journey, the signal strength for the access segments uses Gaussian distributed normalised CNR (carrier-to-noise ratio). This approach was adopted from [72], which was designed for HO testing between satellite and terrestrial systems, and also between terrestrial networks. Therefore, the input matrix X and targeted output matrix Y are as shown:

$$X = \begin{bmatrix} lat_1 & long_1 & RSS_{sat_1} & RSS_{wlan_1} & QoS_1 & BW_1 \\ lat_2 & long_2 & RSS_{sat_2} & RSS_{wlan_2} & QoS_2 & BW_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ lat_{n-1} & long_{n-1} & RSS_{sat_{n-1}} & RSS_{wlan_{n-1}} & QoS_{n-1} & BW_{n-1} \\ lat_n & long_n & RSS_{sat_n} & RSS_{wlan_n} & QoS_n & BW_n \end{bmatrix}$$

$$Y = \begin{bmatrix} TO_{sat_1} & TO_{wlan_1} \\ TO_{sat_2} & TO_{wlan_2} \\ \vdots & \vdots \\ TO_{sat_{n-1}} & TO_{wlan_{n-1}} \\ TO_{sat_n} & TO_{wlan_n} \end{bmatrix}$$

5.3.2 Classifier Architecture

The overview architecture of the PCNN system is shown in Figure 5-6. The six input parameters will be processed by the PCNN system to determine the corresponding targeted output's value. The PCNN system is a back propagation MLP, which consists of the input layer, a single hidden layer and an output layer. The topology of the NN system is shown in Figure 5-7.

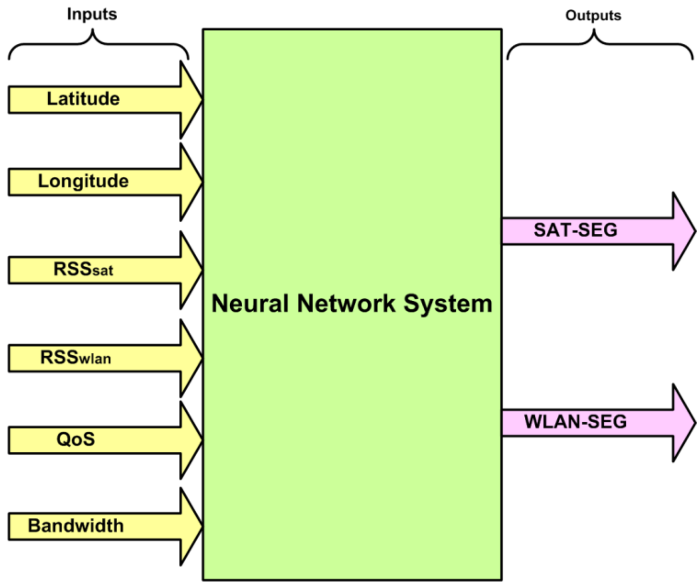

Figure 5-6: Pattern Classification NN System for HD

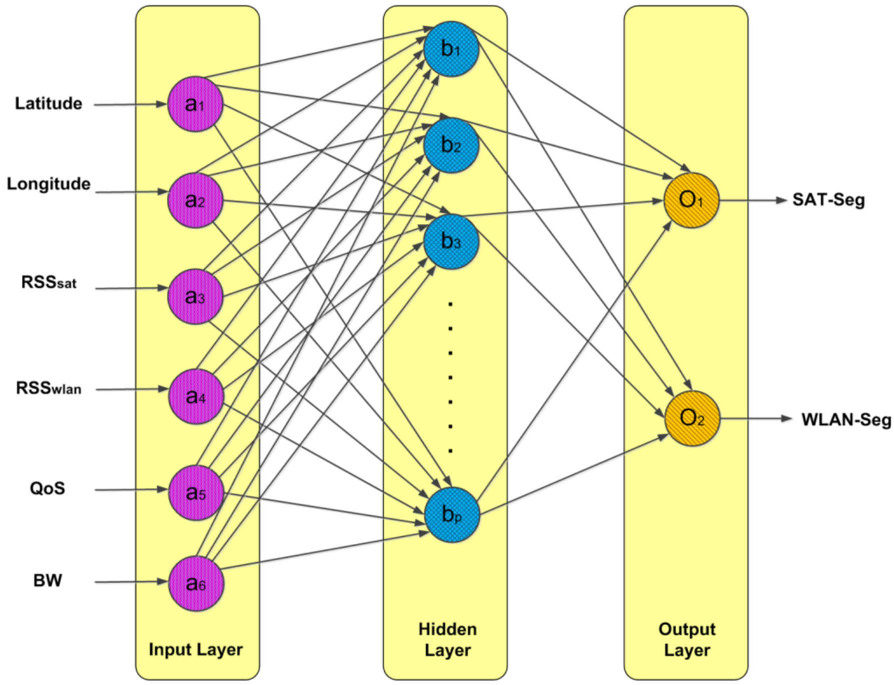

Figure 5-7: Topology of the NN network used for the HD algorithm

The NN system shown in Figure 5-6 is required to identify which access segment is appropriate during the HD phase. This is based on the conditions of the parameters rendered in the dataset, which is used to train the behaviour of the PCNN system. To ensure the dataset reflects the expected behaviour of the trained classifier, the pink boxes in Figure 5-8 depicts the relationship in the mapping of the input parameters to the output parameters based on the specified criteria. As shown in Figure 5-8, the classifier is trained to provide higher priority to the train's location coordinates when determining which access segment to handover. The algorithm will then consider the expected conditions for the satellite RSS, W-LAN RSS, QoS and BW, which is depicted in Figure 5-8. The targeted outputs are either a binary value of 0 or 1, which is determined by the PCNN system. The PCNN system will only allow one output to be of value '1' at any time, for example, if satellite segment output (SAT-SEG) is 1 then W-LAN segment output (WLAN-SEG) will be 0. If the WLAN-SEG output is a 1 then *vice versa* occurs.

For this research, two datasets were specified and applied to the PCNN. The first dataset, termed Data1, was used to train, validate and test the PCNN. Based on the sample data, Data1, the trained PCNN should not only be able to determine which access segment is appropriate during the HD phase, but also be able to generalise for conditions that were not specified in the dataset. Therefore, to evaluate the performance of the trained PCNN, an additional dataset, known as Data2, will be required. Data2 will consist of information that exists from the data used in the training and also non-existing information. Both datasets are available in Appendix C.

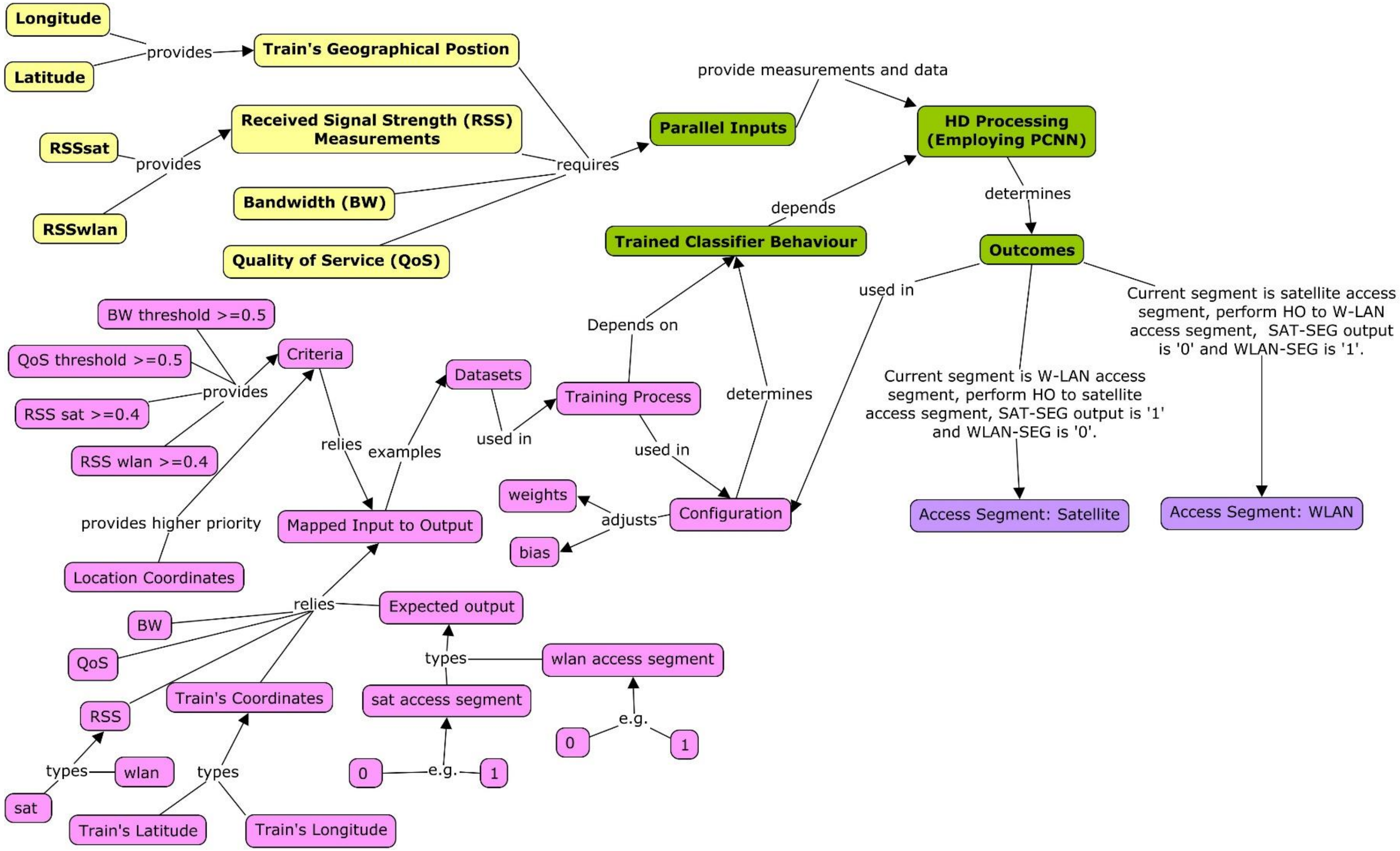

Figure 5-8: Handover Decision (HD) Algorithm Concept Map

The performance of the PCNN corresponds to the number of hidden nodes in the hidden layer, based on the learning algorithm employed. Therefore, it will be necessary to determine the minimum number of hidden nodes that will allow the NN system to achieve optimal generalisation behaviour without overtraining the system. Overtraining of the system, also known as overfitting, occurs when the system has learnt all the training dataset and the training error that occurs has decreased to a significantly small value; however, due to the complexity of the system, when new information is presented to the system, it is unable to generalise and produces large errors.

The selection of hidden nodes for MLPs has been a widely researched topic, as seen in [111-113]; it is an on-going research area as it is not feasible to have a single universal approach for determining the number of hidden nodes in a NN. There are some common guidelines for selecting the number of hidden nodes for a NN system, which are specified as follows:

- The number of hidden neurons in the hidden layer should be between the input layer size and the output layer size [114].
- The hidden layer should not exceed twice the size of the input layer [115].
- It was stated in [116] that as many nodes as dimensions needed is specified to capture 70% to 90% of the variance of the input data set.

However, these guidelines have long been considered to be inadequate as they do not take into consideration the complexity of the activation function, the number of training cases in the dataset, the training algorithm and the

NN architecture [113]. In this research, Data1 was distributed randomly, with 70% of the data used for training the PCNN, and the remaining data split evenly for validation and testing of the NN. Hence, the training dataset for PCNN system consists of 5,686 input/targeted output training pairs (N_{trn}). Based on the outputs (O) to be considered, the number of training equations (N_{trneq}) using Equation 5-17 to calculate will be 11,372.

$$\mathrm{N_{trneq}} = \mathrm{N_{trn}} * \mathrm{O} \qquad \text{Equation 5-17}$$

Due to the number of training equations, the above listed guidelines are not suitable for approximating the number of hidden nodes for this research. Furthermore, in [117], it states that for a single hidden layer feedforward network (SLFN) with regular sigmoidal activation functions, it can take up to *N* number of hidden nodes to learn *N* training samples. However, to prevent overfitting in MATLAB, the chosen number of hidden nodes (H) needs to fulfil the following condition:

$$N_{trneq} \gg N_w \qquad \text{Equation 5-18}$$

N_w = Total number of unknown weights to be estimated

Therefore, Equation 5-19 is used to estimate the upper limit for the number of hidden nodes (H_{ub}) in a PCNN based on the number of training equations, inputs (I) and outputs.

$$H_{ub} = -1 + \mathrm{A} \qquad \text{Equation 5-19}$$

whereby *A* is calculated by using Equation 5-20 and rounded to the nearest integer.

$$\mathrm{A} = \left(N_{trneq} - O\right)/(I + O + 1) \qquad \text{Equation 5-20}$$

Applying Equation 5-19 and Equation 5-20, the calculations for H_{ub} are as shown:

$$
\begin{aligned}
H_{ub} &= -1 + \left(N_{trneq} - O\right)/(I + O + 1) \\
&= -1 + (11372 - 2)/(6 + 2 + 1) \\
&= -1 + (11370/9) \\
H_{ub} &\approx 1262
\end{aligned}
$$

To fulfil the condition in Equation 5-18,

$$H \ll H_{ub} \qquad \text{Equation 5-21}$$

Therefore, based on the guided value of H_{ub}, a heuristic approach is adopted to determine the optimal number of hidden nodes in the hidden layer to achieve good performance from the PCNN. This research will apply three different training algorithms, SCG, RBP and LVM, to the PCNN to compare the performance of the system with respect to the algorithms. Therefore, the number of hidden nodes necessary for the PCNN will differ for each training algorithm. The best performance achieved from the PCNN based on the number of hidden nodes with respect to the training algorithm is shown in Table 5-2. To reduce the complexity and avoid overfitting the PCNN, the optimal hidden nodes for each training algorithm was established through employing the 99.5 % accuracy rate benchmark for HO that is stated in [27]. During training, the PCNN optimises the NN performance by adjusting the connecting weights, i.e. $W_{P,N}$, of each element. Therefore, the total number of unknown weights for each respective algorithm in the PCNN can be determined from Equation 5-22 and is listed in Table 5-2.

$$N_w = [(I + 1) * H] + [(H + 1) * O] \qquad \text{Equation 5-22}$$

Training Algorithm	H	N_W
LVM	76	518
RBP	171	1211
SCG	86	616

Table 5-2: Number of Hidden Nodes (H) and Unknown Weights (Nw) for Each Training Algorithm

The preferred activation function chosen for the PCNN was *tan-sigmoid*, which was discussed in 5.2.1. It was chosen, as tan-sigmoid functions tend to run faster and are a good trade-off for NN, where speed is the essence rather than the exact shape of the transfer function [118].

5.3.3 Performance Function

During the training of the PCNN, the network performance is optimised by adjustment of the weights and biases of the NN. Mean squared error (mse) was selected as the performance function for the training of the PCNN, which calculates the average squared error between the output and the targeted output using Equation 5-23 [119]. The mse is then used to update the weights and biases of the PCNN based on the type of training algorithm applied.

$$mse = \frac{1}{Q}\sum_{j=1}^{Q}\left(t_j - a_j\right)^2$$

Equation 5-23

t = Targeted Outputs

a = Network Outputs

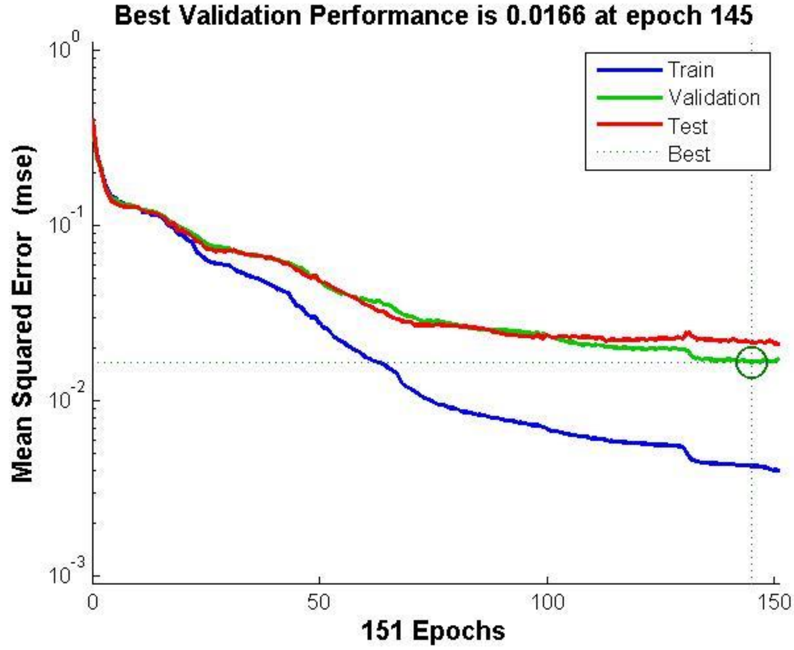

Figure 5-9: Performance Plot of LVM algorithm with 76 Hidden Nodes

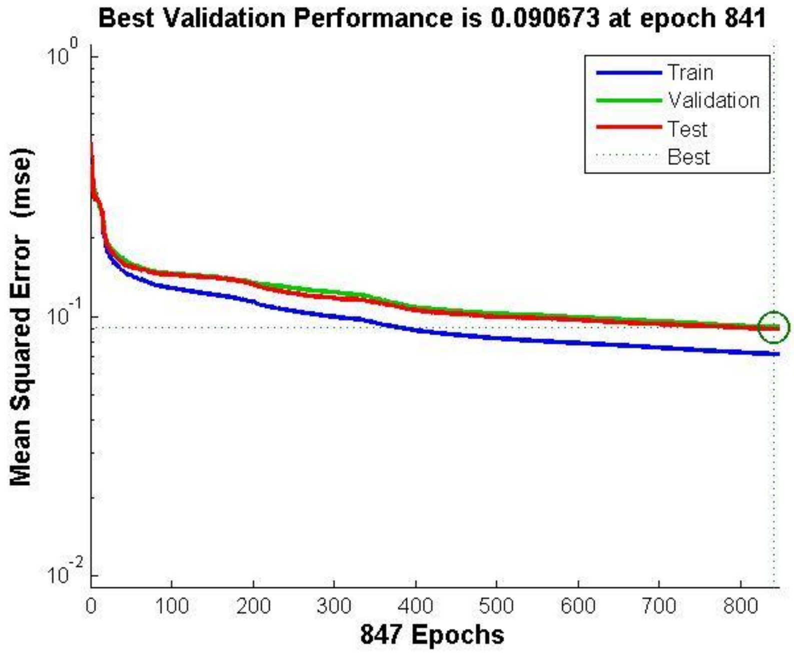

Figure 5-10: Performance Plot of RBP algorithm with 171 Hidden Nodes

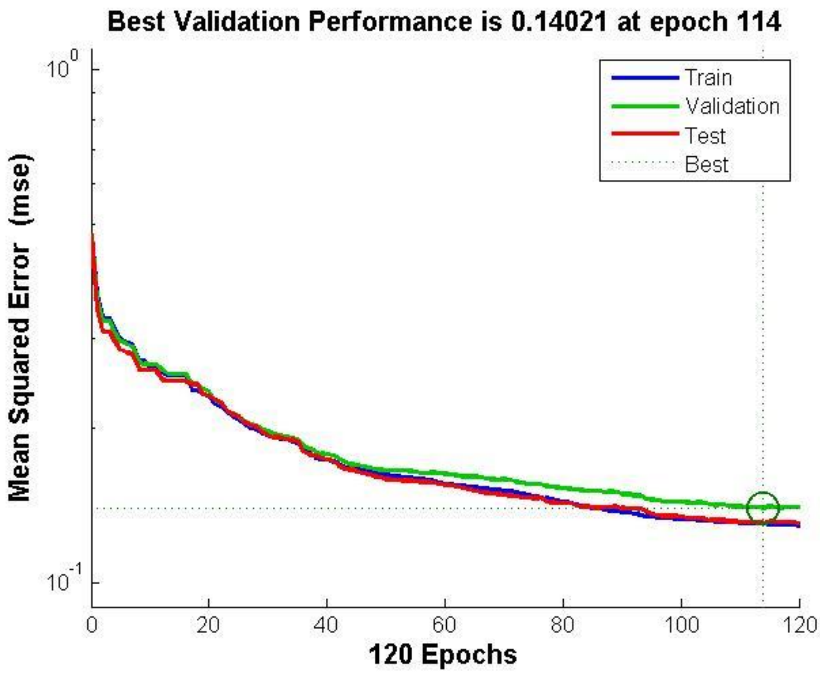

Figure 5-11: Performance Plot of SCG algorithm with 86 Hidden Nodes

Upon completion of the training of the PCNN, the training, validation and test performance plots based on the respective learning algorithm, number of hidden nodes and the selected performance function are plotted. Figure 5-9 shows the LVM training algorithm that consists of 76 hidden nodes and achieved the minimum validation performance of 0.0166 at epoch 145. Figure 5-10 shows the RBP algorithm with 171 hidden nodes applied and the minimum validation performance of 0.090673 was obtained at epoch 841. The performance plot of the SCG algorithm with 86 hidden nodes is shown in Figure 5-11 and the minimum validation performance of 0.14021 was reached at epoch 114. The LVM training algorithm achieved the lowest value of minimum validation performance when compared to RBP and SCG. It also has the least number of weights to be optimised, which implies a less complex system that is capable of generalisation. However, it was observed that RBP and SCG were fast and efficient learning algorithms that were able to train the PCNN with Data1 in a short duration of time. The LVM algorithm, even though was least complex, took the longest duration to finish training the network. The evaluation performance of the PCNN with respect to the respective algorithms and number of hidden nodes will be further elaborated in the next chapter.

5.4 Summary

In this chapter, a background of NN and the parameter selections applied in the PCNN algorithm were described. It was observed that the performance of the PCNN is correlated to the number of hidden notes employed by the training algorithm. It was necessary to establish the optimal number of hidden nodes required for each specific training algorithms and literature has shown that there are no specific methodology that can be applied. Therefore, a heuristic approach was simulated in MATLAB and using the MATLAB NN Toolbox. The approach took into account the 99.5% benchmark in the GSM-R specifications and also the complexity of the PCNN system. The outcomes showed that to achieve good performance in training by the PCNN system, as shown in Table 5-2:

- LVM training algorithm requires 76 hidden nodes.
- RBP training algorithm requires 171 hidden nodes.
- SCG training algorithm requires 86 hidden nodes.

This implies three classifier architectures would need to be evaluated and compared to determine which architecture would provide the best performance and suitability as a HD algorithm for this research study. This lays the groundwork for analysing the performance of the three PCNN architecture in MATLAB. The simulation activities of this research will be addressed in section 6.3.

6 SIMULATION ACTIVITIES

6.1 Scope

In this chapter, the simulation models that were performed using OPNET and MATLAB are presented and the objectives from the OPNET and MATLAB simulation are specified in section 6.2.1 and 6.3.1. The OPNET model focuses on the MM and consists of the location management and handover management procedures that were adopted from [70] (elaborated in Section 6.2). The functional layer and signalling protocols that were specified in chapter 4 will also be modelled in the OPNET simulation and the handover delay performance determined. The simulation approach considers certain aspects of location management because certain functions in HO rely on the functional procedures for location management. However, the main aspects related to the handover management in the OPNET simulation are addressed in this research study.

Based on the findings from section 5, the three PCNN classifier architectures identified will be simulated in MATLAB and presented in Section 6.3. The LVM, RBP and SCG training algorithms will be applied to each architecture. Two datasets will be applied to the classifiers, the first dataset is used for the training, testing and validation phase of the PCNN classifier. The second dataset will be used in evaluating the performance of the trained PCNN classifiers. The outcomes and results that are achieved will then be presented and analysed.

6.2 OPNET Simulation

6.2.1 Simulation Approach

The objectives of the simulation model for handover are to compute the:

- Delay from the initial handover decision phase to the handover execution phase, and;
- Total delay for the handover procedure from the initial handover decision in HI to the switching of the bearer services.

The OPNET simulation focuses on the functional layer. The mapping of the FEs onto the physical devices is shown in Figure 6-1. Further information on each specific FE was discussed in Section 4.5. It can be seen that the model consists of different node models representing each physical device. Each node model will be developed to comprise different modules representing the different FEs. Table 6-1 presents the FEs that were either involved in Location Management or Handover Management, respectively.

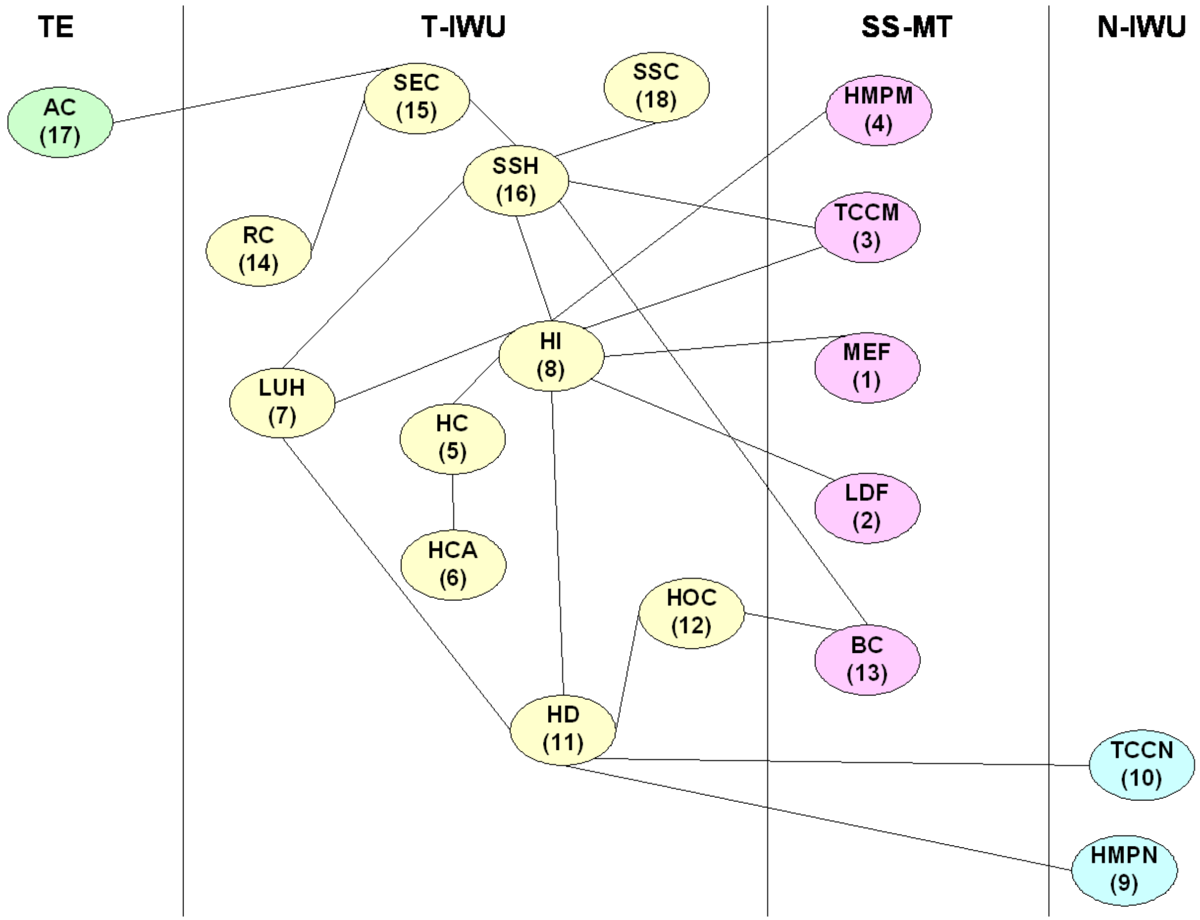

Figure 6-1: Mapping of the functional layer for OPNET Simulation

Serial No.	FE No.	FE	Location Management			Handover Management		
			Location Update	Segment Selection/Reselection	Session Establishment	Handover Initiation	Handover Decision	Handover Execution
1	FE8	MEF				X		
2	FE1	LDF	X			X		
3	FE4	TCCM		X		X		
4	FE5	HMPM				X		
5	FE11	HC				X		
6	FE10	HCA				X		
7	FE3	LUH	X	X		X	X	
8	FE6	HI	X	X		X	X	
9	FE12	HMPN					X	
10	FE13	TCCN					X	
11	FE7	HD				X	X	X
12	FE14	HOC					X	X
13	FE15	BC		X				X
14	FE26	RC			X			
15	FE25	SEC		X	X			
16	FE20	SSH	X	X	X			
17	FE27	AC			X			
18	FE22	SSC		X				

Table 6-1: Functional Entities involved in Mobility Management

6.2.2 Simulation Model Architecture

6.2.2.1 Simulation Project Model

The OPNET simulation model is shown in Figure 6-2. The physical devices are the TE, T-IWU, SAT-MT, WLAN-MT, Satellite Access Network (SAT_ACC), Edge Router (ER), Management Information Database (MIB) and Network Inter-working Unit (N-IWU). The node models of the SAT-MT, WLAN-MT, ER, MIB and N-IWU physical devices developed for the model will be addressed in the following sections.

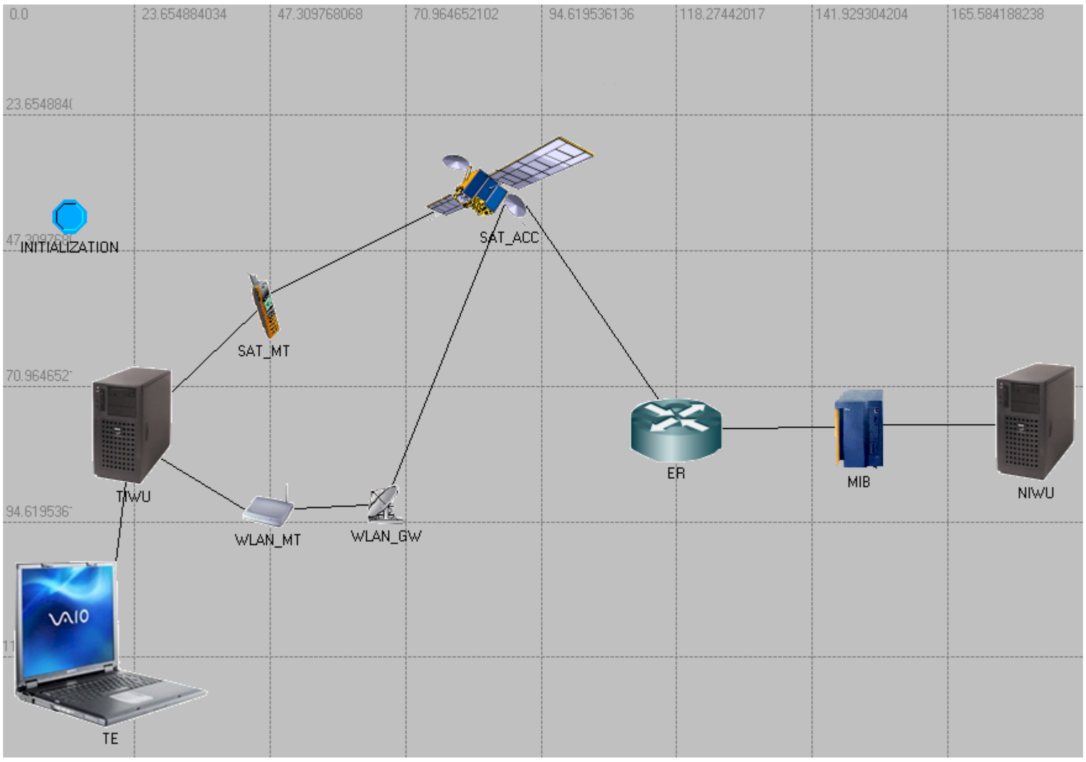

Figure 6-2: Simplified OPNET Simulation Model

6.2.2.2 Mobile Terminals

In the mobility management procedures, the T-IWU needs to interact with the SAT-MT and WLAN-MT to obtain information, such as the geographic coordinates and RSS of the MT. A generic node model was developed, so that it can be modelled either as a SAT-MT or WLAN-MT. Thus, the characteristic of the MT is to be defined by setting the different parameters in the attributes of the modules. Figure 6-3 shows the MT node model that comprises the LDF, LDB, BC, TCCM, MEF and HMPM modules.

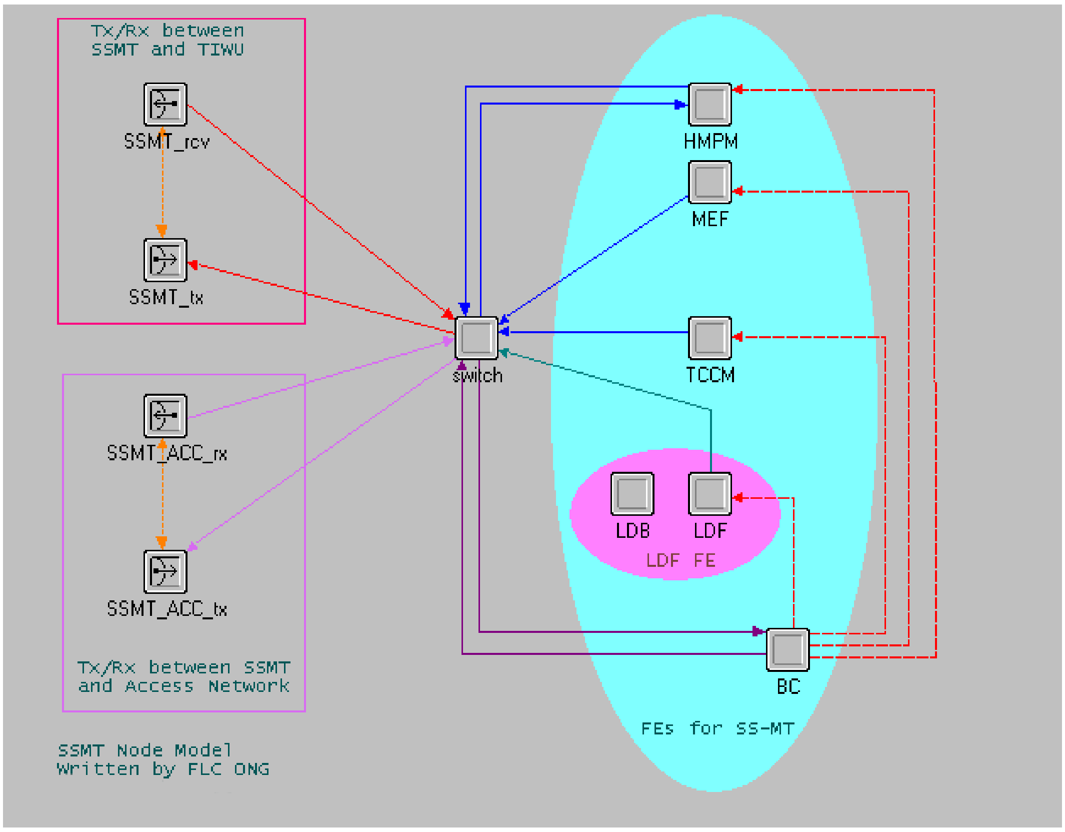

Figure 6-3: Mobile Terminal (MT) Node Model

The descriptions of the modules are as follows:

- **TCCM** - When the MT is inactive, this module provides information, i.e. Signal Strength and Delay, to the T-IWU periodically. The signal strength and delay information is retrieved externally from the satellite access network and noise is also introduced into the signal strength. The period for sending information to the T-IWU is set in the TCCM_TIME_PERIOD attribute. For example, if the TCCM_TIME_PERIOD is set to 5 s, then every 5 s, TCCM forwards information to T-IWU SSH and HI.

- **HMPM** - For handover initiation, HI sends a request to HMPM. HMPM, upon receiving the request, responds to HI with the MT's profile containing relevant information, such as the bandwidth required.
- **MEF** - When the MT is active, this module sends measurements periodically to HI. Similar to TCCM, this information is retrieved externally from the satellite access network and induced with noise. The MEF_TIME_PERIOD also needs to be set to a value, for example 6 s, so that the MT will periodically send the information to HI.
- **LDB** - In this module, a scenario file is developed to simulate the changes of the geographic position of the train and forwards the value to LDF, where it is used as the current co-ordinates of the train. The co-ordinates chosen were from Rome (Latitude 41.89°N and Longitude 12.5°E) to Florence (Latitude 43.78°N and Longitude 11.24°E). The journey on a high-speed train from Rome to Florence is approximately two hours; it is assumed that the train is at a station from 120 s to 300 s and from 700 s to 880 s. During this period, the co-ordinates remain unchanged, as the train is not moving. This is depicted in Figure 6-4.
- **LDF** – When the MT is active, this module sends the current geographic positioning information of the train to HI periodically. The co-ordinates of the train are retrieved from LDB and consist of the Latitude and Longitude. Similar to MEF, the period when the information is sent to HI is based on the period set in the LDF_TIMER_PERIOD_HI attribute.
- **BC** – When BC receives a CONNECT or RELEASE request from T-IWU, this entity processes the request and returns the result to T-IWU. When BC is connected and becomes the active segment, it triggers the MEF

and LDF function. When BC connection is released and becomes inactive, it notifies the status of BC to MEF, LDF, HMPM and TCCM.

- **Switch** - This module is responsible for switching the incoming packets to the destined FE.

#Time(s);	Latitude(Degree,N);	Longitude(Degree, E)
0.0000;	41.8900;	12.5000
20.0000;	41.8950;	12.4967
40.0000;	41.8999;	12.4934
60.0000;	41.9049;	12.4901
80.0000;	41.9099;	12.4867
100.0000;	41.9149;	12.4834
120.0000;	41.9198;	12.4801
140.0000;	41.9198;	12.4801
160.0000;	41.9198;	12.4801
180.0000;	41.9198;	12.4801
200.0000;	41.9198;	12.4801
220.0000;	41.9198;	12.4801
240.0000;	41.9198;	12.4801
260.0000;	41.9198;	12.4801
280.0000;	41.9198;	12.4801
300.0000;	41.9198;	12.4801
320.0000;	41.9696;	12.4469
340.0000;	41.9746;	12.4436
360.0000;	41.9795;	12.4403
380.0000;	41.9845;	12.4370
400.0000;	41.9895;	12.4337
420.0000;	41.9944;	12.4304
440.0000;	41.9994;	12.4271
460.0000;	42.0044;	12.4237
480.0000;	42.0094;	12.4204
500.0000;	42.0143;	12.4171
520.0000;	42.0193;	12.4138
540.0000;	42.0243;	12.4105
560.0000;	42.0293;	12.4072
580.0000;	42.0342;	12.4038
600.0000;	42.0392;	12.4005
620.0000;	42.0442;	12.3972
640.0000;	42.0492;	12.3939
660.0000;	42.0541;	12.3906
680.0000;	42.0591;	12.3873
700.0000;	42.0641;	12.3839
720.0000;	42.0641;	12.3839
740.0000;	42.0641;	12.3839
760.0000;	42.0641;	12.3839
780.0000;	42.0641;	12.3839
800.0000;	42.0641;	12.3839
820.0000;	42.0641;	12.3839
840.0000;	42.0641;	12.3839
860.0000;	42.0641;	12.3839
880.0000;	42.0641;	12.3839
900.0000;	42.1138;	12.3508
920.0000;	42.1188;	12.3475
940.0000;	42.1238;	12.3442
960.0000;	42.1287;	12.3408

Figure 6-4: Example of Scenario File used by LDB

With reference to Figure 6-2 , for the W-LAN access segment, a gateway (GW) is required to access the satellite network. The node model of the GW is shown in Figure 6-5. It forwards the packets received according to the destination address.

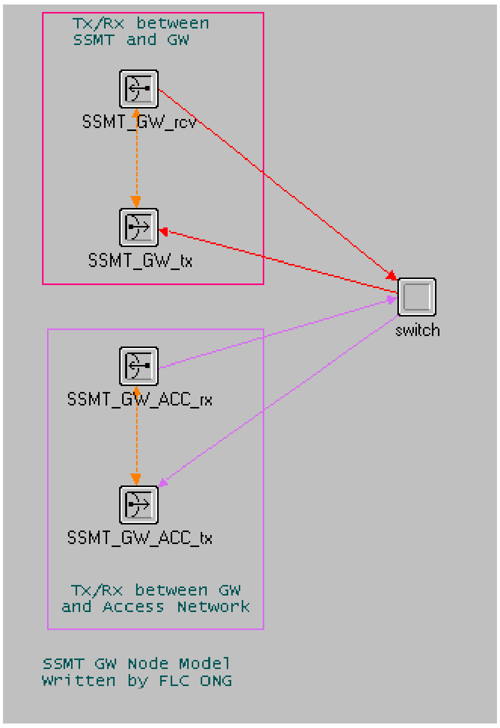

Figure 6-5: Gateway for WLAN Access Segment Node Model

6.2.2.3 Edge Router

The edge router (ER) is responsible for forwarding the packets either from the satellite access network to the N-IWU or vice versa, according to the destination address. A First-In-First-Out (FIFO) queue is used to buffer the packets and the service rate of the queue is set in the Service_Rate attribute.

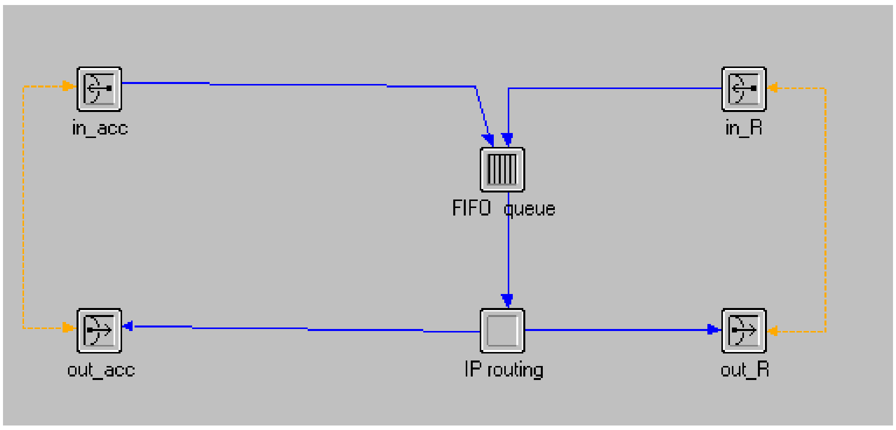

Figure 6-6: Edge Router (ER) Node Model

6.2.2.4 *Management Information Database*

The MIB comprises three modules, i.e. Database (DDB), Management Database (MDB) and switch. Figure 6-7 depicts the MIB node model. Descriptions of the modules follow:

- **DDB** - Similar to LDB, a scenario file is developed to simulate the resource availability (such as bandwidth availability) of the satellite access network. DDB retrieves the resource availability information and forwards it to MIB.
- **MDB** - This module retrieves information from DDB and periodically sends resource availability information of the satellite access network to TCCN in N-IWU.
- **Switch** - This module is responsible for switching the incoming packets to the destined FE.

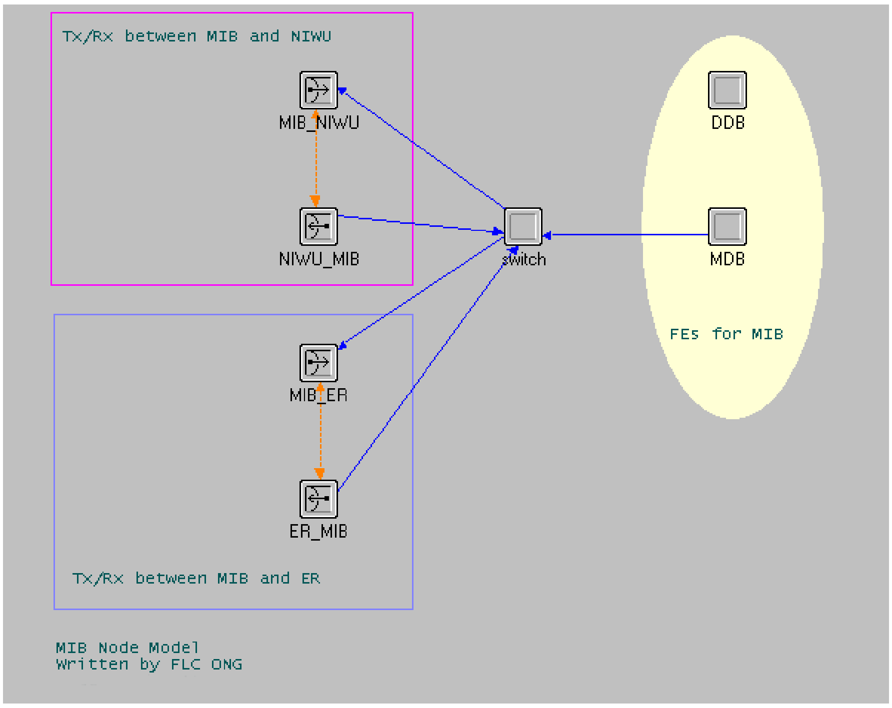

Figure 6-7: Management Information Database (MIB) Node Model

6.2.2.5 Network Inter-working Unit

The N-IWU consists of the TCCN and HMPN modules. It interacts with the T-IWU and receives resource information of the satellite access network from MIB periodically.

- **TCCN** - This resource information of the satellite network is constantly updated and sent from MIB to TCCN periodically. When TCCN receives a packet from MIB, it reads and stores the information. During the HD phase, HD in the T-IWU sends a resource information request to TCCN. When TCCN receives the request, it retrieves the latest resource information and sends the response back to HD.
- **HMPN** - When the T-IWU is executing the handover decision phase, it also sends a Service_Data request to HMPN. HD requests from HMPN for the service data information, such as the bandwidth supported when using either the satellite access segment or W-LAN access segment, perceived from the network. HMPN then stores the service data in the functional packet and forwards the response to HD.
- **NIWU-Switch** - This module is responsible for switching the incoming packets to the destined FE.

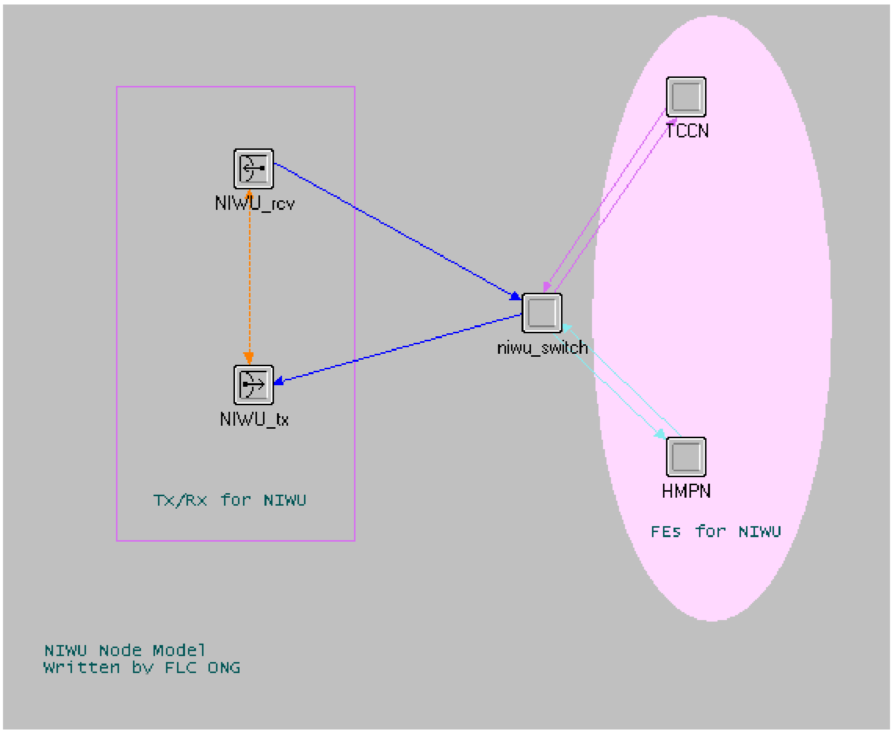

Figure 6-8: N-IWU Node Model

6.2.3 Results and Observations of OPNET Simulation

6.2.3.1 Assignment of Attributes of Models

The attributes that are specified for the different FEs in the physical devices are addressed in this section.

- **Terminal Inter-working Unit (T-IWU)**

The parameters to be assigned in the T-IWU are shown in Table 6-2. The value assigned for the *Signal Threshold for Handover* parameter in HI is equal to RSS_{thres}, as stated in Section 5.3.1. The *satellite and W-LAN present* parameters indicate the status of the respective segment in the network (i.e. available or not available). The value assigned to the *time between segment availability checks* parameter implies how often the segment availability database in LUH is updated. The *signal strength* *threshold* parameter is the threshold value used in the segment selection procedures. The *IP_ADDR_DDB* scenario file is a database, which stores the IP addresses, and when TE requests for a CoA from the T-IWU, the IP addresses will be retrieved and the information will be passed onto the TE. The *Threshold_DDB* scenario file contains the threshold values of the different parameters, such as RSS, which will be used for the handover. The *Velocity_DDB* scenario file is used for simulating the train's velocity, which will be required for determining when a hard handover should be performed.

FE Module	**Attribute**	**Assigned Value**
HI	Signal Threshold for Handover	0.3
IP_ADDR_DDB	Scenario File	fif_IP_Address
LUH	Satellite Present	YES (or NO)
LUH	WLAN Present	YES (or NO)
LUH	Time between Segment Availability Checks (s)	60
SSC	Signal Threshold	0.1
Threshold_DDB	Scenario File	fif_tiwu_ho_threshold
Velocity_DDB	Scenario File	fif_tiwu_velocity

Table 6-2: T-IWU Parameters Assignment

- **Mobile Terminal (MT)**

Since a generic node model has been designed, the attributes definition for some of the modules will be different when the model is specified as a SAT-MT or WLAN-MT. For example, the HMPM module provides the segment specific MT's profile information. Hence, when the node model represents the SAT-MT, the BW_SAT_MT and Priority attributes are assigned a value, as the attributes depict the required bandwidth and priority of the SAT-MT respectively. In this case, the BW_WLAN_MT attribute is not applicable. Table 6-3 presents the attributes definition for the segment specific MT. Further information of the other modules' attributes definitions are discussed in Section 6.2.2.2.

FE Module	Attribute	Assigned Value for SAT-MT	Assigned Value for WLAN-MT
HMPM	BW_SAT_MT (Mbps)	10.0	NA
HMPM	BW_WLAN_MT (Mbps)	NA	11.0
HMPM	Priority Segment	1	0
MEF	MEF_Time_Period_HI (s)	6.0	6.0
MEF	Sig Variance	0.5	0.5
TCCM	Sig Variance	0.5	0.5
TCCM	TCCM_Time_Period_HI (s)	5.0	5.0
LDB	Scenario File	fif_SSMT_LDF	fif_SSMT_LDF
LDF	LDF_Time_Period_HI (s)	4.0	4.0
BC	Response Time (s)	0.5	0.6
BC	Variance	1.0	1.0

Table 6-3: Mobile Terminal (MT) Parameters Assignment

- **Satellite Access Network, Edge Router and N-IWU**

The satellite access network, edge router and N-IWU assignments for the different attributes are shown, respectively, in Table 6-4. Table 6-5 and Table 6-6.

FE Module	Attribute	Assigned Value
acc_config_sat	Link Bitrate DW (bps)	2,000,000
acc_config_sat	Link Bitrate UP (bps)	2, 000,000
acc_config_sat	Network Capacity (bps)	300,000,000
acc_config_sat	BG_Utilisation_File	fif_bg_test
acc_config_wlan	Link Bitrate DW (bps)	2,000,000
acc_config_wlan	Link Bitrate UP (bps)	2,000,000
acc_config_wlan	Network Capacity (bps)	300,000,000
acc_config_wlan	BG_Utilisation_File	fif_bg_test
Upd_ext_sat	Scenario File	fif_sc_SAT_integrated
Upd_ext_wlan	Scenario File	fif_sc_WLAN_integrated

Table 6-4: Satellite Access Network Parameters Assignment

FE Module	Attribute	Assigned Value
FIFO_queue	Service rate (bps)	10,000

Table 6-5: Edge Router Parameters Assignment

FE Module	Attribute	Assigned Value
HMPN	Bandwidth_SAT_MT (Mbps)	4.0
HMPN	Bandwidth_WLAN_MT_SAT	2.0

Table 6-6: N-IWU Parameters Assignment

6.2.3.2 Simulation Results and Analysis

The simulation takes into consideration the train entering and exiting two train stations during its journey. Therefore, four handover processes are performed. The first and third handover procedures (i.e. handover from satellite segment to W-LAN segment) are performed when the train is entering the train station and the second and fourth handover procedures (i.e. handover from W-LAN segment to satellite segment) are performed when the train is exiting the train station. This is depicted in Figure 6-2.

- **Numerical Results**

The total handover delay can be computed by using Equation 6-1.

$$T_{total\_ho\_delay} = T_{hi\_delay} + T_{hd\_delay} + T_{hoc\_delay} \qquad \text{Equation 6-1}$$

where $T_{total\_ho\_delay}$ refers to the total handover duration to complete the handover process, T_{hi_delay} denotes the duration when HI is initiated until HD is triggered, T_{hd_delay} denotes the duration when HD starts until HOC is triggered and T_{hoc_delay} represents the duration when HOC starts until HOC is completed.

Based on [92], the duration for sending a message in lossless conditions is determined by Equation 6-2:

$$\begin{aligned} T_{S1} = T_{h1} = T_{lossless} & \qquad \text{Equation 6-2} \\ = T_{trans} + T_{prop\_wl} + T_{prop\_wd} + T_{proc} & \end{aligned}$$

where $T_{lossless}$ refers to the time required to send a message between the two relevant FEs under lossless conditions; T_{trans}, the size of the message/link bit rate, denotes the time to transmit the message packet; T_{prop_wl} denotes the propagation delay due to the wireless link; T_{prop_wd} refers to the propagation delay due to the wired link; and T_{proc} refers to the processing time.

The propagation delay due to the wired link, T_{prop_wd}, can be computed using the following equation:

$$T_{prop(D1\ to\ D2)} = \frac{d}{v} \qquad \text{Equation 6-3}$$

where $T_{prop(D1\ to\ D2)}$ refers to the propagation time over the wired link between two devices (D1 and D2); *d* denotes the separation distance between the two devices in metres and *v* refers to the velocity of propagation in a wired cable (i.e. 2 x 10^8 m/s).

Assuming that the separation distance between the two devices is 100 m, T_{prop_wd} is equivalent to 0.5 µs.

The value of T_{trans} is given by Equation 6-4:

$$T_{trans(D1\ to\ D2)} = \frac{DS}{TR} \qquad \text{Equation 6-4}$$

where $T_{trans(D1\ to\ D2)}$ refers to the transmission time between two devices, *DS* refers to the data size and *TR* denotes the transmission rate specified for the transmission between the two devices.

Handover from Satellite to W-LAN

Parameters	Values
Data Size (bits)	752
Transmission rate from T-IWU to SAT-MT	100 Mbps
Transmission rate from T-IWU to WLAN-MT	12 Mbps
Propagation time through the satellite access network, $T_{prop\_wl\ (sat)}$	250 ms
Propagation time through the wired links, T_{prop_wd}	0.5 µs
Response time for BC in the MT due to BC connection request from T-IWU, $T_{bc\_dist\_response}$	0.6s

Table 6-7: N-IWU Parameters Assignment

Using Equation 6-1, Equation 6-2, Equation 6-3 and Equation 6-4, $T_{total\_ho\_delay}$ can be computed as follows:

$$T_{hi\_delay} = \left(T_{trans\ (TIWU\ to\ SAT\_MT)} + T_{prop\_wd}\right) * 2$$

$$= (7.52\ \mu s + 0.5\ \mu s) * 2 = 16.04\ \mu s$$

$T_{trans(TIWU\ to\ SAT\_MT)}$ and T_{prop_wired} values are multiplied by two because in the HI Phase, HI in the T-IWU sends a request to HMPM, and HMPM will then provide the required information in the response to T-IWU. The communication between the SAT-MT and T-IWU is through a wired link (i.e. 100Base-T), which allows T_{prop_wl} to be discounted. T_{proc} is negligible because the process time obtained from the simulation was within the nano-seconds range and this does not really have a significant effect on the delay calculated.

$$T_{hd\_delay} = \{[(T_{trans\,(TIWU\ to\ SAT\_MT)} + T_{trans\,(ER\ to\ MIB)} + T_{trans\,(MIB\ to\ NIWU)}) * 2] + T_{prop\_wl(conn)} + T_{prop\_wd(total)}\} * 2$$

$$= [(7.52\ \mu s + 7.52\ \mu s + 7.52\ \mu s) + 250\ ms + (0.5\ \mu s * 3)] * 2$$

$$= 0.50009624\ s$$

During the HD phase, the T-IWU requests information from TCCN and HMPN in the N-IWU. Therefore, the calculation above takes into account additional factors, such as the T_{prop_wd} from ER to N-IWU and transmission time from ER to N-IWU. The $T_{prop\_wl(conn)}$ represents the satellite round-trip time delay, 250 ms, which mainly contributes to T_{hd_delay}.

$$T_{hoc\_delay} = [(T_{trans\,(TIWU\ to\ SAT\_MT)} + T_{trans\,(TIWU\ to\ WLAN\_MT)} + T_{prop\_wd(total)}) * 2] + T_{dist\_bc\_response}$$

$$= [(15.04\ \mu s + 125.3334\ \mu s) + 2\ \mu s] * 2 + 0.6\ s = 0.60028475\ s$$

For the Handover Execution phase, T-IWU establishes a connection to the WLAN-MT and releases the connection from SAT-MT. Hence, additional factors such as the transmission time for both MTs and T_{prop_wired} for both links were taken into consideration. It can be seen that the main delay contribution for handover execution is due to the bearer connection establishment, which is $T_{dist\_bc\_response}$.

Therefore, employing Equation 6-1, the total handover duration, $T_{total\_ho\_delay}$, can be determined as 1.100397 s, which can be approximated to 1.10 s.

Handover from W-LAN to Satellite

Applying the parameters from Table 6-7, and based on the numerical analysis shown above, the handover delay for W-LAN to Satellite can be calculated as shown.

$$T_{hi\_delay} = \left(T_{trans\ (TIWU\ to\ WLAN\_MT)} + T_{prop\_wd}\right) * 2$$

$$= (62.6667\ \mu s + 0.5\ \mu s) * 2 = 0.12633\ ms$$

$$T_{hd\_delay} = \Big\{\Big[\Big(T_{trans\ (TIWU\ to\ WLAN\_MT)} + T_{trans\ (ER\ to\ MIB)}$$

$$+ T_{trans\ (MIB\ to\ NIWU)}\Big) * 2\Big] + T_{prop\_wl(conn)} + T_{prop\_wd(total)}\Big\} * 2$$

$$= [(125.3334\ \mu s + 30.08\ \mu s) + (250\ ms + 68.3636364\ \mu s)$$

$$+ (0.5\ \mu s * 6)] * 2 = 0.50045339\ s$$

$$T_{hoc\_delay} = \Big[\Big(T_{trans\ (TIWU\ to\ SAT\_MT)} + T_{trans\ (TIWU\ to\ WLAN\_MT)}$$

$$+ T_{prop\_wd(total)}\Big) * 2\Big] + T_{dist\_bc\_response}$$

$$= [(15.04\ \mu s + 125.3334\ \mu s) + 2\ \mu s] * 2 + 0.6\ s = 0.60028475\ s$$

Based on Equation 6-1, the total handover duration, $T_{total\_ho\_delay}$, can be determined as 1.100864 s, which can be approximated to 1.10 s.

- **Handover Initiation Phase Results**

For simulation purposes, the Handover (HO) Initiation End Time, which differs to what the term T_{hi_delay} is defined above, implies when the handover process is completed. With reference to Figure 4-11, this when the HD phase provides an acknowledgment response back to the HO.EXE.REQ request that was sent from HI to HD. Therefore, the HO Initiation Signalling Delay can also be taken as the total time duration to complete the handover procedures. The results for the handover process is shown in Table 6-8; the average of the total handover process is approximately 1.08 s. The total handover delay (i.e. $T_{total\_ho\_delay}$) values gathered (i.e. handover from satellite to W-LAN and vice versa) were approximately the same as the calculations performed in the numerical results section.

HO Type	HO Initiation Signalling Delay (s)
From Satellite to W-LAN	0.92471
From W-LAN to Satellite	1.11067
From Satellite to W-LAN	1.19598
From W-LAN to Satellite	1.08497

Table 6-8: Results of Handover Initiation Procedure

- **Handover Decision Phase Results**

In the simulation, the HD phase, which is dissimilar to the definition of T_{hd_delay} from the numerical results paragraph above, is completed when the HO.EXE.CMD acknowledgement response, refer to Figure 4-12, is forwarded from HOC to HD upon completion of the handover execution phase. Therefore, the approximate duration to complete the Handover Decision phase is 1.08 s and is derived from the results tabulated in Table 6-9.

HO Type	HO Decision Signalling Delay (s)
From Satellite to W-LAN	0.92453
From W-LAN to Satellite	1.11065
From Satellite to W-LAN	1.19579
From W-LAN to Satellite	1.08494

Table 6-9: Results of Handover Decision Procedure

- **Handover Execution Phase Results**

The results for the handover execution phase are presented in Table 6-10; the duration for the Handover Execution phase to be completed is approximately 0.5095 s.

HO Type	HO Execution Signalling Delay (s)
From Satellite to W-LAN	0.44096
From W-LAN to Satellite	0.50002
From Satellite to W-LAN	0.60019
From W-LAN to Satellite	0.49675

Table 6-10: Results of Handover Execution Procedure

6.3 MATLAB Simulation

6.3.1 Overview

As mentioned in Chapter 5, a PCNN system was adopted for the handover decision algorithm. Based on the six inputs, the system determines and classifies which access segment should be used in the handover decision phase. The training, validation and testing simulation employs the dataset, Data1, as specified in Section 5.3.1. To evaluate the trained PCNN, another dataset, Data2, is used. Data2 was applied for the handover in the OPNET simulation and will be applied to the trained PCNN system. For the training, validation, testing and evaluation simulation, three training algorithms, LVM, RBP and SCG, and the different number of hidden nodes addressed in Section 5.3.2 are taken into consideration. The simulated feedforward networks, which employ the pattern recognition network from the MATLAB neural network toolbox and consist of the different number of hidden nodes, are shown in Figure 6-9, Figure 6-10 and Figure 6-11, respectively.

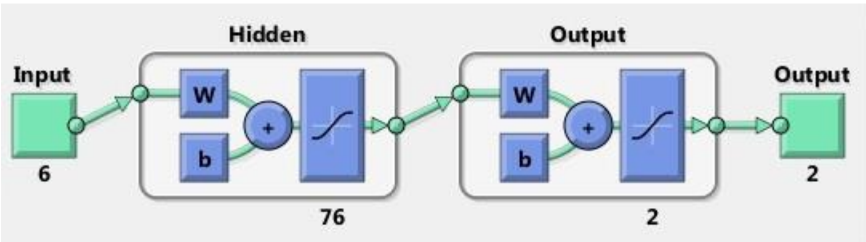

Figure 6-9: Simulation Model with 76 Hidden Nodes

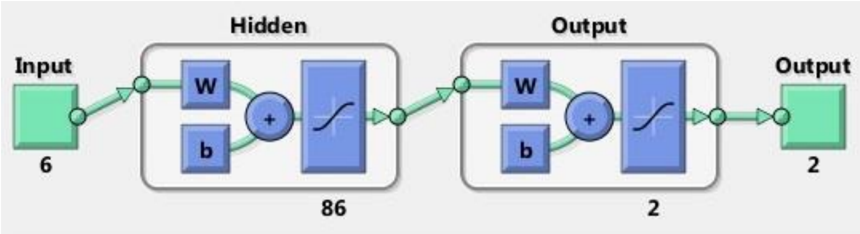

Figure 6-10: Simulation Model with 86 Hidden Nodes

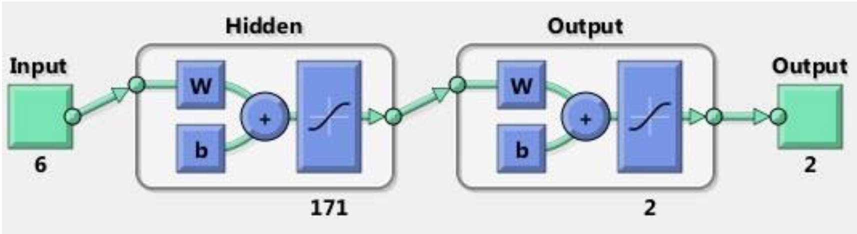

Figure 6-11: Simulation Model with 171 Hidden Nodes

The main objectives of the MATLAB simulation are to:

- Determine the training, validation and testing performance of the PCNN taking into account the different number of hidden nodes and the training algorithms, which are addressed in Section 6.3.2 .
- Evaluate the generalised performance of the trained PCNN when new data, Data2, is presented to the NN. This is discussed in Section 8.3.3.

The training, validation and testing performance of the PCNN system will largely be presented in the form of a Confusion Plot [120]. Confusion plots will also be used to display the performance of the simulated trained PCNN system. In addition, a ROC Plot [121] will also be employed to present the performance of the trained PCNN system. These two plots are commonly used for performance evaluation of a classification NN system.

6.3.2 Training, Validation and Testing Results

6.3.2.1 PCNN Simulation Model with 76 Hidden Nodes

The performance of the PCNN system with 76 hidden nodes with respect to the three training algorithms, LVM, RBP and SCG, will be discussed in this section. Data1 was applied to the PCNN system for training, validation and testing. The resulting performance of each training algorithm that is applied to the PCNN system is displayed in a confusion plot, also known as a confusion matrix.

Figure 6-12 shows the confusion matrices of the LVM training algorithm with 76 hidden nodes. The class value '1' on the output and target class axis represents the satellite access segment and class '2' implies the W-LAN access segment. It can been seen that the PCNN system was able to classify 5627 of the data samples correctly out of 5686. Therefore, as shown in the blue square of the all confusion matrix in Figure 6-12, the PCNN system was able to achieve an overall 99% correct classification. As mentioned in Section 5, 70% of the dataset was used for training, 15% was for validation and the remaining 15% was for testing the system. Therefore, 3980 data samples were used for training, 853 data samples were each respectively applied in validating and testing the PCNN system. The breakdown performance of the PCNN system for each stage is also plotted in a confusion matrix and shown in Figure 6-12.

Figure 6-12: Training, Validation, Testing and Overall Confusion Matrix for LVM Training Algorithm with 76 Hidden Nodes

In training, the training confusion matrix shows that the PCNN system classified 24 data samples (also known by the termed targets in a confusion matrix) incorrectly, giving an overall incorrect classification of 0.6%. There were 2492 class 1 data samples and 14 were incorrectly assigned to class 2, thereby giving 99.4% correct class 1 targets classification. For class 2, there were 1488 data samples and the PCNN system correctly classified 99.3% of class 2 targets.

The training confusion matrix also shows that 2488 data samples were allocated to the output class 1 and 10 data samples from class 2 were incorrectly assigned to class 1, giving a correct classification performance of 99.6%. For output class 2, 14 out of the 1492 data samples allocated to output class 2 were incorrectly assigned to class 2 and produced a correct classification performance of 99.1%. Therefore, during training, the overall correct classification performance shown in the blue square of the training confusion matrix is 99.4%.

Figure 6-13: Training, Validation, Testing and Overall Confusion Matrix for RBP Training Algorithm with 76 Hidden Nodes

In the validation stage, 14 out of 853 data samples were incorrectly classified. Therefore, the PCNN system, as shown in the validation confusion matrix in Figure 6-12, achieved an overall correct classification performance of 98.4%. For the testing stage, the PCNN system correctly classified 832 out of the 853 data samples, which can be seen by the green squares in the test confusion matrix in Figure 6-12. Therefore, the PCNN system achieved an overall correct classification in the testing stage of 97.5%.

The confusion matrices for the PCNN system employing the RBP training algorithm with 76 hidden nodes is shown in Figure 6-13. When the RBP training algorithm is employed in the PCNN system, it was noted that 1010 data samples were incorrectly assigned and the system was only able to achieve an overall correct classification of 82.2%. The breakdown of overall correct classification for the training, validation and testing of the PCNN system are 81.9%, 82.5% and 83.6%, respectively. It was also observed that on average the PCNN system showed approximately 28% incorrect classification for class 2 targets across all three stages, which is significantly higher in comparison to the LVM learning algorithm.

For the SCG training algorithm with 76 hidden nodes, the PCNN system was not able to generalise accurately, resulting in NaN (Not-a-Number) outputs shown in the confusion matrices as shown in Figure 6-14.

It was observed that 76 hidden nodes were not sufficient for the PCNN system to learn and generalise the training samples in Data1 when the SCG learning algorithm was applied. Therefore, a significantly high percentage of error classification was observed across all stages and also the overall result. During the course of the simulation, it was noted that the PCNN system employing the SCG training algorithm produced results without any NaN outputs only when the number of hidden nodes was 80 and above.

Figure 6-14: Training, Validation, Testing and Overall Confusion Matrix for SCG Training Algorithm with 76 Hidden Nodes

The PCNN system employing 76 hidden nodes and the LVM training algorithm yield the best performance in training, validation and testing stages compared to the RBP and SCG training algorithms. Moreover, the PCNN system also produced significantly lower error classification across all sectors compared to the RBP and SCG training algorithms and resulted in an overall correct classification performance of 99%. The PCNN system with 76 hidden nodes employing the LVM training algorithm will be further evaluated with Data2 in Section 6.3.3.1. This will determine the generalised behaviour of the PCNN system when old and new data are presented to the system.

6.3.2.2 PCNN Simulation Model with 86 Hidden Nodes

The architecture of using 86 hidden nodes in the PCNN system will be elaborated in this section. The results achieved when applying the three learning algorithms in this architecture will be plotted in confusion matrices and are also presented in this section.

Figure 6-15: Training, Validation, Testing and Overall Confusion Matrix for LVM Training Algorithm with 86 Hidden Nodes

In Figure 6-15, the confusion matrices for the PCNN system with 86 hidden nodes and employing the LVM training algorithm are shown. It can be seen that, with 89 hidden nodes, the overall classification performance of the training, validation and testing stages were 98.1%, 96.4% and 97.5%, respectively. With this architecture, it can be seen that the PCNN system seems to give, as shown in Figure 6-15, more error in generalising class 2 targets across all stages compared to the architecture in Section 6.3.2.1 employing the LVM training algorithm. An overall 105 incorrect classifications were performed by the PCNN system for class 2 data samples. There was a concern if overfitting had occurred with this architecture, however, the performance plot in Figure 6-16, shows that the validation and test curves were quite similar and no overfitting had occured. Nonetheless, the PCNN system still generated a good performance and provided an overall correct classification of 97.7%.

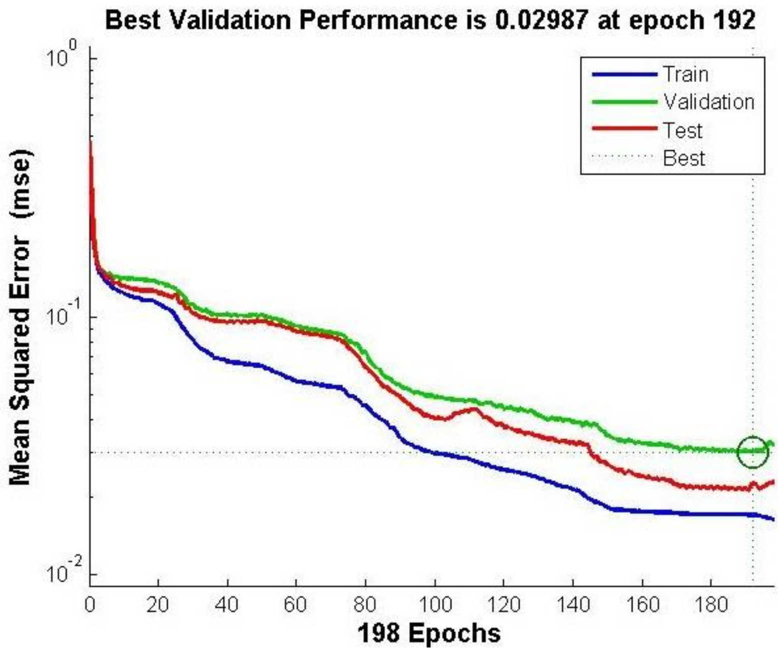

Figure 6-16: Performance Plot of LVM algorithm with 86 Hidden Nodes

The performance results that were achieved with this architecture employing the RBP training algorithm are shown in Figure 6-17. It can be seen that the overall performance, which is 82.9%, is quite similar to the architecture employing the same algorithm in Section 6.3.2.1. The overall incorrect classification performance had decreased slightly, with 975 data samples incorrectly classified by the PCNN system compared to the 1010 incorrect classified data sample in Section 6.3.2.1. Therefore, with this architecture employing the RBP algorithm, there was a 0.7% improvement in the overall classification performance of the PCNN system. The overall correct classification performance for each stage with this architecture is also quite similar, with less than 2% difference observed between each stage.

Figure 6-17: Training, Validation, Testing and Overall Confusion Matrix for RBP Training Algorithm with 86 Hidden Nodes

In Figure 6-18, the results achieved by applying the SCG training algorithm to the PCNN system with 86 hidden nodes are shown. The overall correct classification performance of the PCNN system for the training, validation and testing stages are 82.1%, 81.9% and 82.5% respectively, which displays quite a stable overall correct classification performance with less than 1% difference between the stages. The PCNN system showed an overall correct classification performance of 82.1%. Compared to the same algorithm applied in the architecture described in Section 6.3.2.1, the PCNN system produces no NaN results and showed significant improvement in the learning and generalisation capabilities. Moreover, the results obtained for the SCG algorithm in this architecture displayed the best performance when compared to the architectures in Section 6.3.2.1 and 6.3.2.3, respectively.

Figure 6-18: Training, Validation, Testing and Overall Confusion Matrix for SCG Training Algorithm with 86 Hidden Nodes

It can be seen that in this architecture, both the RBP and SCG algorithm show quite similar performace in the confusion matrices. Both algorithms show an average of less than 28% chance of incorrectly classifying class 2 data samples and approximately 88% chance of correctly classifying class

1 data samples. However, it can be seen that the LVM still outperforms the RBP and SCG learning algorithms in this architecture.

6.3.2.3 PCNN Simulation Model with 171 Hidden Nodes

The performance results achieved by the PCNN system consisting of 171 hidden nodes with the respective training algorithms, LVM, RBP and SCG, will be discussed in this section. This includes the overall performance confusion matrices and breakdown of the training, validation and testing stages confusion matrices for each training algorithm.

Figure 6-19: Training, Validation, Testing and Overall Confusion Matrix for LVM Training Algorithm with 171 Hidden Nodes

Figure 6-19 shows the performance when the LVM training algorithm was applied to the PCNN system with 171 hidden nodes. The PCNN system shows an overall correct classification of 84.2% out of the 5686 data samples. The overall incorrect classification of class 1 and class 2 targets was approximately 12% and 23%, respectively. It can be seen that the PCNN system falls behind in performance when compared to the LVM algorithm being applied to the architectures in Section 6.3.2.1 and 6.3.2.2.

Figure 6-20: Training, Validation, Testing and Overall Confusion Matrix for RBP Training Algorithm with 171 Hidden Nodes

The performances attained by the PCNN system with 171 hidden nodes when the RBP training algorithm is applied is depicted in Figure 6-20. The system achieved an overall correct classification performance of 90.2%. The resulting correct classification performance of the training, validation and testing stages are 91%, 88% and 88.4%, respectively. The overall incorrect classification was approximately 7% for class 1 targets and 15% for class 2 targets. In this architecture, the RBP learning algorithm produced significantly better results when compared to the same algorithm applied to the architectures in Section 6.3.2.1 and 6.3.2.2.

Figure 6-21: Training, Validation, Testing and Overall Confusion Matrix for SCG Training Algorithm with 171 Hidden Nodes

Figure 6-21 shows the results that were obtained when the SCG algorithm was applied to the PCNN system with 171 hidden nodes. The overall correct classification produced by the PCNN system was 76.7%. This architecture when employing the SCG algorithm gave the lowest performance outcome among the three learning algorithms and also had an average of 23% incorrect classification performance across the training, validation and testing stages.

With this architecture, it can be seen that the RBP training algorithm outperforms the LVM and SCG training algorithms, with an overall correct classification performance of 90.2%. This is the best performance that the RBP algorithm has achieved between the three architectures in Section 6.3.2. However, in comparison to the LVM algorithm, the RBP algorithm employs a larger number of hidden nodes to achieve this performance. Based on the training, validation and testing analyses achieved in Section 6.3.2, the evaluation of the PCNN system to generalise from old and new data samples with respect to the three learning algorithms will be carried out in Section 6.3.3.

6.3.3 Evaluation Results and Observations

6.3.3.1 PCNN Simulation Model with 76 Hidden Nodes

After the PCNN system was trained, it was necessary to evaluate the learning and generalisation behaviour of the trained system. Therefore, as mentioned in Section 6.3.1, the evaluation performance of the trained system in accordance with the different hidden nodes architecture will employ another dataset, Data2. Data2 consists of 417 old and new data samples, which will aid in determining the performance of the trained PCNN system during the evaluation process. In this section, the trained PCNN that consists of 76 hidden nodes will be addressed. The confusion matrices of the trained PCNN system employing the different training algorithms will also be presented. An optimum classifier should achieve the point of zero on the x-axis and one on the y-axis of a ROC plot, which is known as the (0,1) point. Therefore, the ROC plots will also be used to determine the performance of the trained PCNN system with respect to the different training algorithms used.

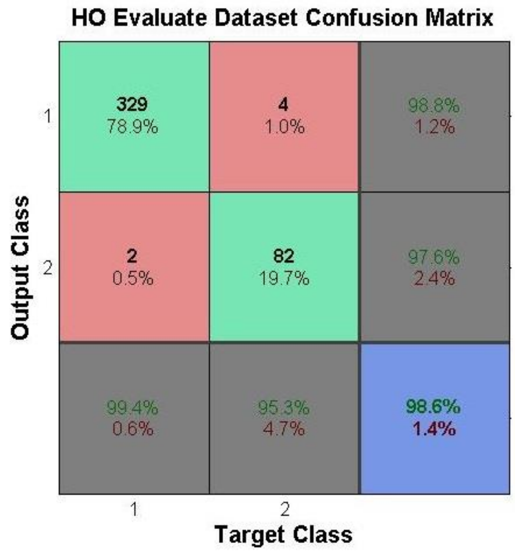

Figure 6-22: Overall Classification Confusion Matrix for Evaluation of the LVM Training Algorithm with 76 Hidden Nodes

Figure 6-22 depicts the overall classification matrix of the PCNN system that employs the LVM training algorithm. It can be seen that when Data2 was applied to the trained PCNN system, the correct overall classification was 411 data samples out of 417 data samples. The trained PCNN system achieved a percentage of 98.6% of correct overall classification. The trained system showed an incorrect classification of 0.6% class 1 data samples and 4.7% class 2 data samples. It can be seen that this architecture, employing the LVM training algorithm, showed that the system was able to generalise from new unseen data and also obtain an extremely high accuracy in classifying the data samples.

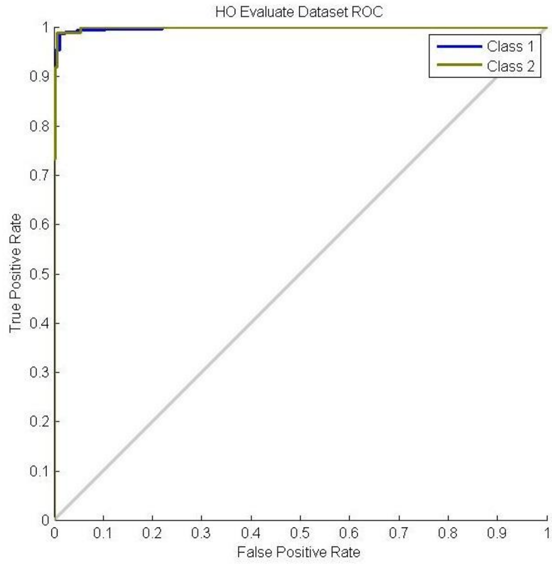

Figure 6-23: ROC Plot for Evaluation of the LVM Training Algorithm with 76 Hidden Nodes

Moreover, this was further highlighted in the ROC plot, as shown in Figure 6-23. The plot shows that for class 1 and class 2 targets, the trained PCNN system achieved an almost perfect classification performance, as the ROC curves for both class 1 and class 2 data samples were significantly close to the (0,1) point. Based on the confusion matrix and ROC plot, the results achieved imply that the classifier shows high effectiveness and efficiency in classifying the data samples precisely.

The performance results that were obtained when the RBP Training algorithm was applied to the trained PCNN system are shown in Figure 6-24 and Figure 6-25. In the training, validation and testing phase, as discussed in Section 6.3.2.1, this architecture achieved an overall 82.2% correct classification performance. It can be seen from Figure 6-24 that the classifier was able to generalise from the data samples in Data2, as it was able to classify 392 of the data samples correctly. The trained PCNN system performed well as it achieved an overall correct classification of 94%. The overall error classification was 6%; with most of the error classification related to class 2 targets. This corresponded with the results that were obtained during the training, validation and testing stages, as described in Section 6.3.2.1.

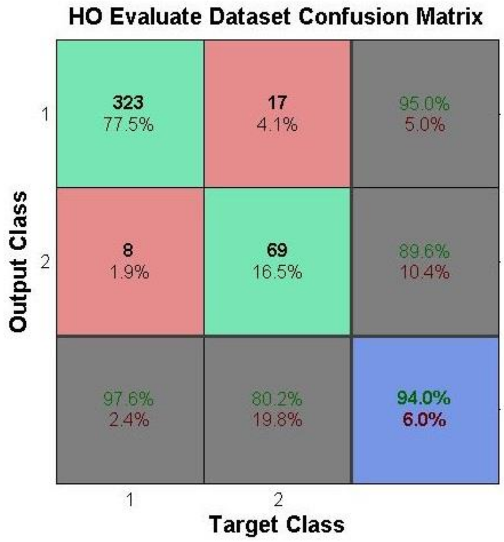

Figure 6-24: Overall Classification Confusion Matrix for Evaluation of the RBP Training Algorithm with 76 Hidden Nodes

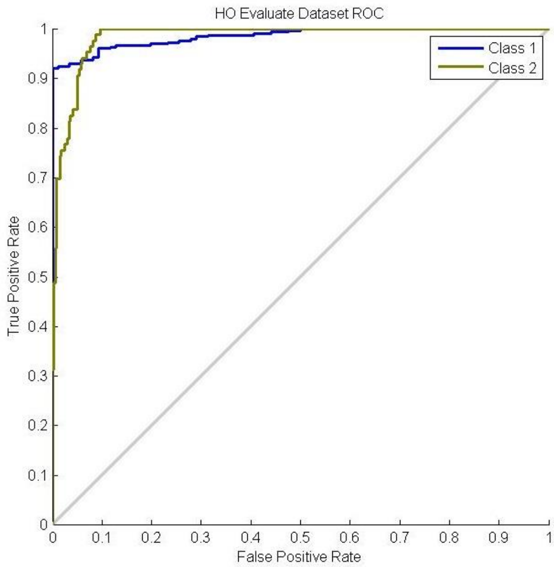

Figure 6-25: ROC Plot for Evaluation of the RBP Training Algorithm with 76 Hidden Nodes

The results were also reflected in Figure 6-25, as the ROC plot shows good accuracy in the trained PCNN system for class 1 and class 2 targets. Therefore, with this architecture and training algorithm, the classifier is still capable of performing well during evaluation even though it did achieve relatively good results during the training, validation and testing stages.

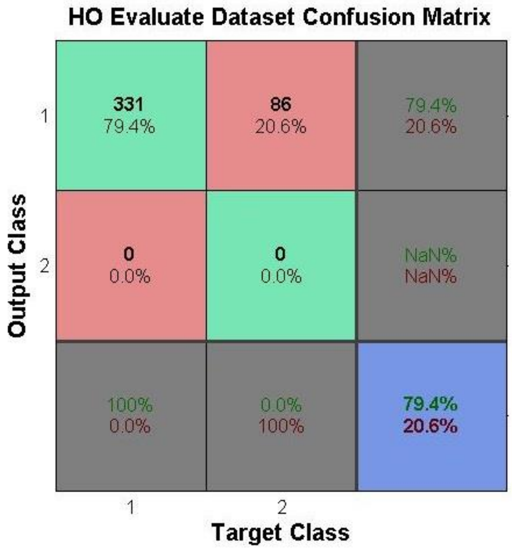

Figure 6-26: Overall Classification Confusion Matrix for Evaluation of the SCG Training Algorithm with 76 Hidden Nodes

As addressed in Section 6.3.2.1, the training, validation and testing results that were achieved for this architecture using the SCG training algorithm were unreliable. This was mainly due to underfitting in the PCNN system and implies that the system is not able to learn and generalise the data samples correctly. Therefore, it is expected that the results that are obtained during the evaluation process will be significantly poor and flawed.

The outcomes that were attained when the SCG training algorithm was applied to the trained PCNN system are illustrated in Figure 6-26 and Figure 6-27. The confusion matrix of the evaluated PCNN system, refer to Figure 6-26, shows that the trained PCNN system achieved an overall correct classification performance of 79.4%. The behaviour that the trained PCNN system was showing was classifying all data samples to be class 1 and not being able to classify class 2 targets correctly. Therefore, this implies that the accuracy of the trained PCNN system was flawed, which is also highlighted in the ROC plots shown in Figure 6-27.

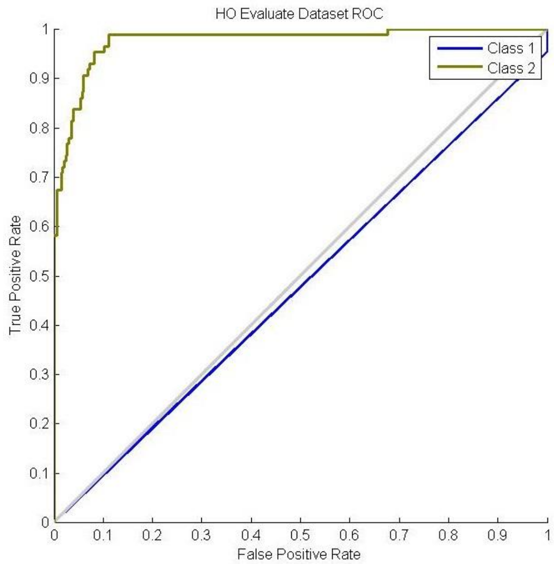

Figure 6-27: ROC Plot for Evaluation of the SCG Training Algorithm with 76 Hidden Nodes

In the evaluation process of the trained PCNN system with 76 hidden nodes, it can be determined that the architecture that adopted the LVM training algorithm achieved the best performance of approximately 99% accuracy and attained an almost perfect classification of the data samples. Moreover, it showed that when the trained PCNN system was presented with new data, it was able to generalise and classify the data precisely. The trained PCNN system that employed the RBP training algorithm also showed good evaluation performance of 94%. The classification error of 6% attained by the system showed that even though during the training, validation and testing stages the PCNN system did not achieve high overall classification performances, it was still able to generalise new and old data. With regards to using the SCG training algorithm for this architecture, the results that were achieved highlighted that it was not suitable to be deployed in a 76 hidden nodes PCNN system. The outcomes illustrated that the system showed underfitting and could not generalise. Moreover, significant errors and flaws occurred during the training, validation, testing and evaluation stages.

6.3.3.2 PCNN Simulation Model with 86 Hidden Nodes

This section presents the results that are achieved when the three training algorithms are applied to the trained PCNN system with 86 Hidden Nodes. In Figure 6-28, the confusion matrix shows the performance of the evaluated architecture that employs the LVM training algorithm. It can be seen that the classifer performed well and classified 404 out of the 417 data samples correctly. The incorrect classification was six class 1 data samples and seven class 2 data samples, therefore, achieving an overall correct classification performance of 96.9%.

The ROC plot in Figure 6-29 also showed that the classifier had good accuracy and was an effective classifer. Even though this classifer did not perform as well as the trained PCNN system employing the same training algorithm in Section 6.3.3.1, it does show that the system showed an acceptable performance and was able to generalise the dataset well.

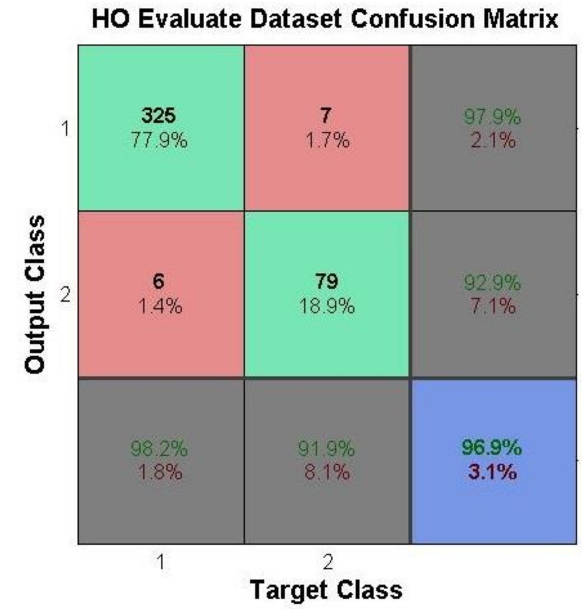

Figure 6-28: Overall Classification Confusion Matrix for Evaluation of the LVM Training Algorithm with 86 Hidden Nodes

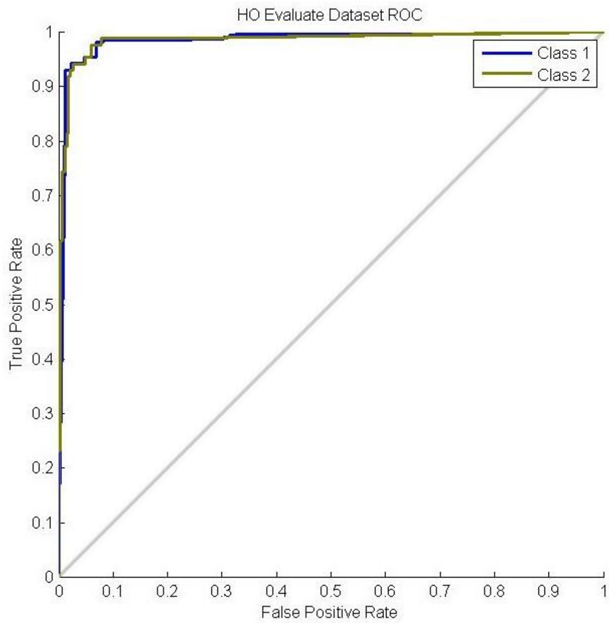

Figure 6-29: ROC Plot for Evaluation of the LVM Training Algorithm with 86 Hidden Nodes

The results that were obtained when the RBP training algorithm was applied to the trained PCNN system is shown in Figure 6-30 and Figure 6-31, respectively. In Section 6.3.2.2, the classifier employing this learning algorithm showed a relatively good performance in the training, validation and testing stages. Based on the respective results shown in Figure 6-30 and Figure 6-31, in the evaluation stage, it can be seen that there was an improvement in the classifer performance. The confusion matrix in Figure 6-30 illustrates that this classifier architecture, during evaluation, was able to classify 391 out of the 417 data samples correctly; 10 out of the 331 class 1 data samples and 16 out of the 86 class 2 data samples were incorrectly classified. The overall correct classification of 93.8% was achieved in the evaluation process, which is a good performance. This is also reflected in the ROC plot, shown in Figure 6-31, which validates the results of the classifier results that were shown in the confusion matrix.

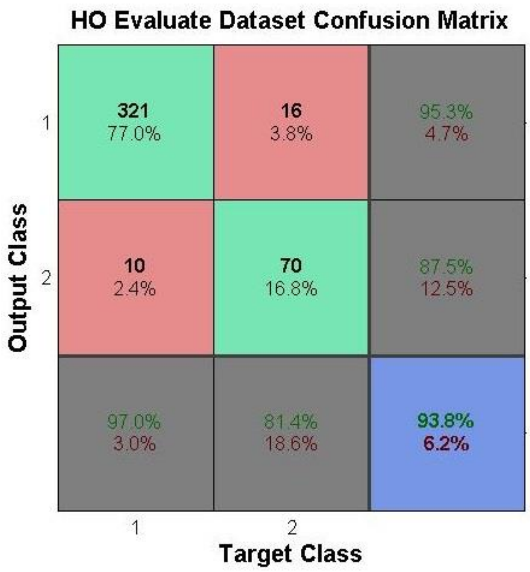

Figure 6-30: Overall Classification Confusion Matrix for Evaluation of the RBP Training Algorithm with 86 Hidden Nodes

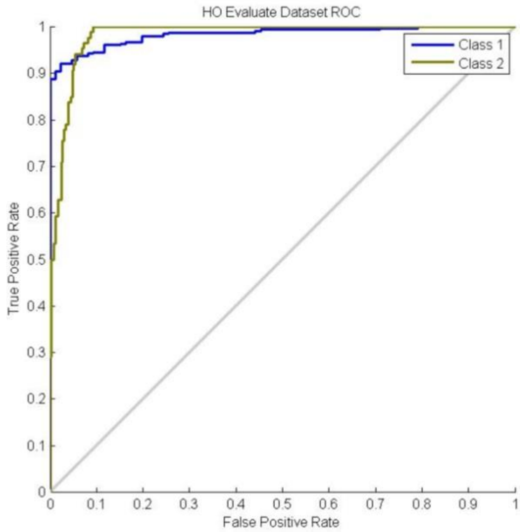

Figure 6-31: ROC Plot for Evaluation of the RBP Training Algorithm with 86 Hidden Nodes

Figure 6-32 and Figure 6-33 show the performance results that were attained when the SCG training algorithm was applied to the classifer with 86 hidden nodes during the evaluation stage. Compared to the results that were achieved in Section 6.3.2.2, there was an improvement in the overall classfication performance. The classifier, during the evaluation process, was able to correctly classify 393 data samples out of the 417 data samples in Data2. Therefore, achieving an overall correct classification performance of 94.2% and displaying a good performance in generalising old and new data. The ROC plot, shown in Figure 6-33, also validates the results that were obtained by the confusion matrix and shows the accuracy of the classifer.

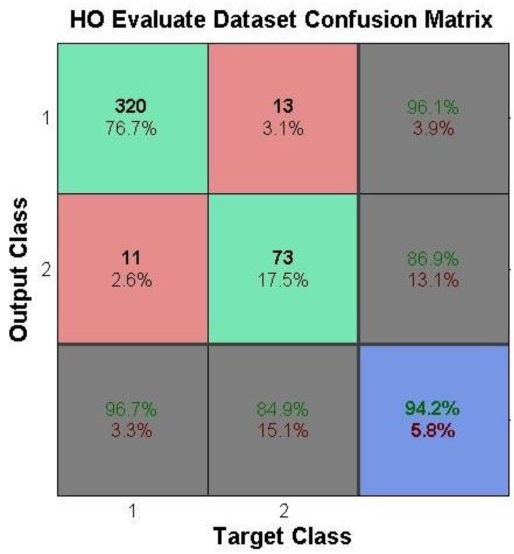

Figure 6-32: Overall Classification Confusion Matrix for Evaluation of the SCG Training Algorithm with 86 Hidden Nodes

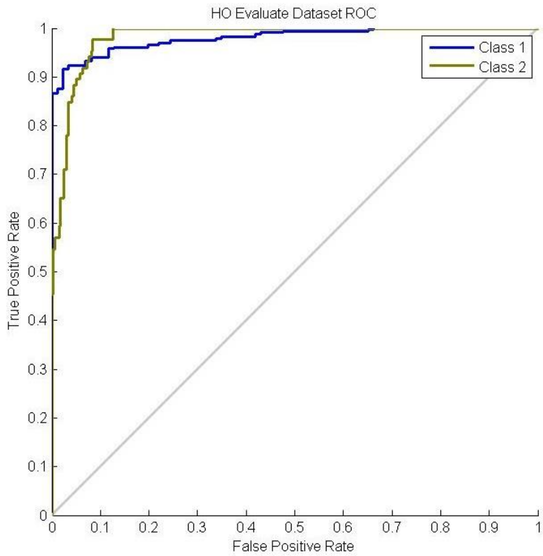

Figure 6-33: ROC Plot for Evaluation of the SCG Training Algorithm with 86 Hidden Nodes

With regards to the evaluation of this classifier architecture, the trained PCNN system shows that all training algorithms were capable of generalising old and new data. The classifier displayed good performance across all three training algorithms. The best outcome was achieved by the LVM training algorithm with an approximate overall correct classification of

97%. Both RBP and SCG training algorithms obtained an approximate accuracy of 94%, which is similar to the performance results that were achieved in the training, validation and testing stage of the same architecture in Section 6.3.2.2.

6.3.3.3 PCNN Simulation Model with 171 Hidden Nodes

The evaluation of the trained classifier consisting of 171 hidden nodes and employing the three different training algorithms will be elaborated in this section. The evaluation performance of the classifier employing the LVM training algorithm is illustrated in Figure 6-34 and Figure 6-35, respectively. The confusion matrix, refer to Figure 6-34, depicted that the classifier was capable of identifying correctly 401 out of the 417 data samples. The classifier incorrectly classified eight class 1 targets and eight class 2 targets, which gave an overall incorrect classification of 3.6%.

In contrast to the performance achieved by the classifier in Section 6.3.2.3, there is an overall improvement in the correct classification performance of 12%. Taking into comparison the different classifier architectures that employ the LVM training algorithm in the evaluation stage, the results obtained by this classifier is only 0.7% lower than the classifier addressed in Section 6.3.3.2 and 2.4% difference from the classifier addressed in Section 6.3.3.1. Therefore, whilst in the training, validation and testing stage, the performance of the classifier significantly differs from the other classifier using the same training algorithm, it can be determined that the performance achieved by this classifier in the evaluation stage is effective and acceptable. This is further substantiated by the results that are obtained in the ROC plot shown in Figure 6-35.

Figure 6-34: Overall Classification Confusion Matrix for Evaluation of the LVM Training Algorithm with 171 Hidden Nodes

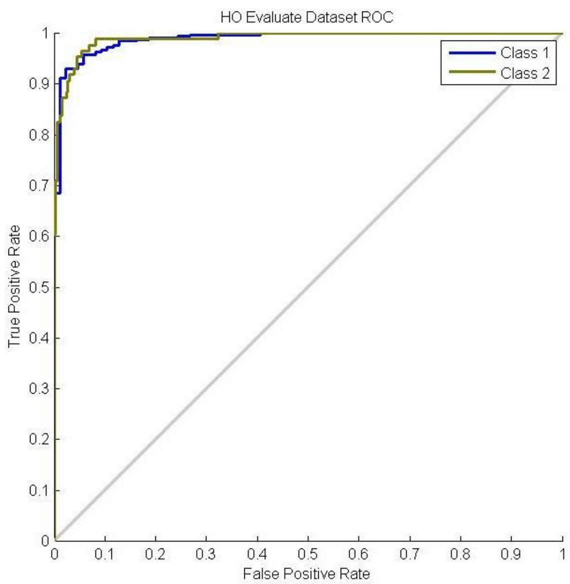

Figure 6-35: ROC Plot for Evaluation of the LVM Training Algorithm with 171 Hidden Nodes

The evaluation performance achieved by the classifier using the RBP training algorithm is shown in Figure 6-36 and Figure 6-37, respectively. Based on the result shown in Figure 6-36, the classifier was able to accurately distinguished 410 out of the 417 data samples. The incorrect classification was three for class 1 targets and four for class 2 targets, giving an overall accurate classification performance of 98.3%. The ROC plot shown in Figure 6-37, illustrates that the classifier is very close to the (0,1) point, which shows high precision and accuracy in the classifier.

Moreover, it can be seen that this classifier performed the best among all the trained PCNN systems that adopted the RBP training algorithm in the evaluation phase. This was also similar to the results obtained by the PCNN system in the training, validation and testing phases in Section 6.3.2.3.

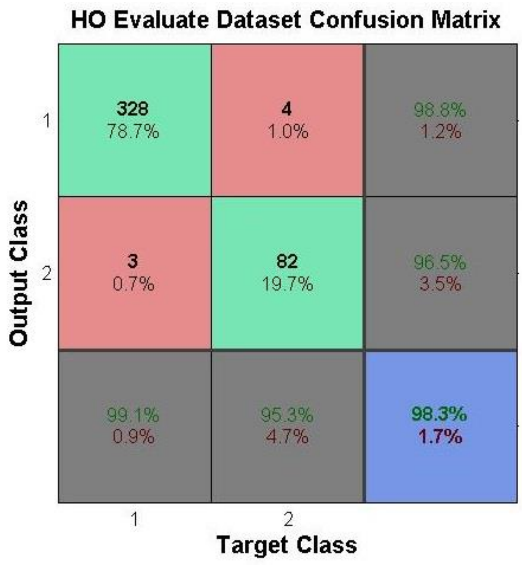

Figure 6-36: Overall Classification Confusion Matrix for Evaluation of the RBP Training Algorithm with 171 Hidden Nodes

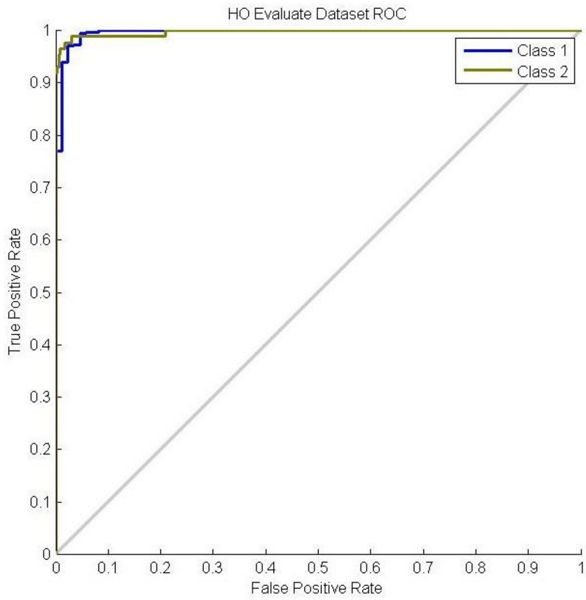

Figure 6-37: ROC Plot for Evaluation of the RBP Training Algorithm with 171 Hidden Nodes

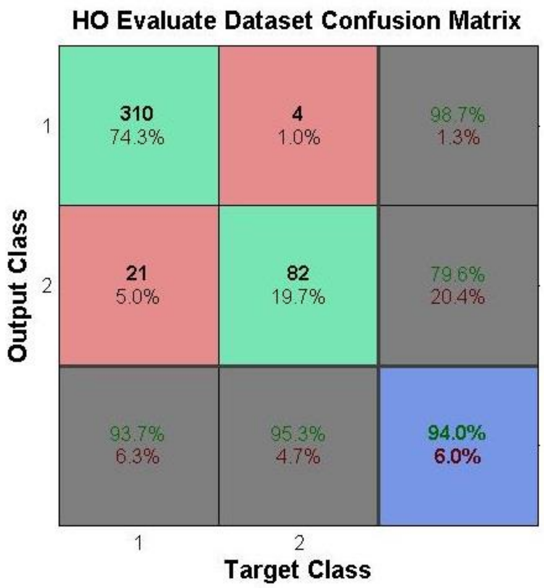

Figure 6-38: Overall Classification Confusion Matrix for Evaluation of the SCG Training Algorithm with 171 Hidden Nodes

Figure 6-38 and Figure 6-39 illustrate the confusion matrix and ROC plot of the evaluated results attained by the trained PCNN system with 171 hidden nodes using the SCG training algorithm. The confusion matrix in Figure 6-38 shows that this classifier has a higher error rate in determining class 1 targets than class 2 targets, which was also observed in the training, validation and testing phase in Section 6.3.2.3. Moreover, the results achieved by this classifier show that even though the performance achieved in the training, validation and testing phase was only 76.7%, it was still able to generalise the data samples and attain a correct classification performance of 94% during the evaluation phase. This is further affirmed by the accuracy performance of the classifier that is illustrated in the ROC plot in Figure 6-39.

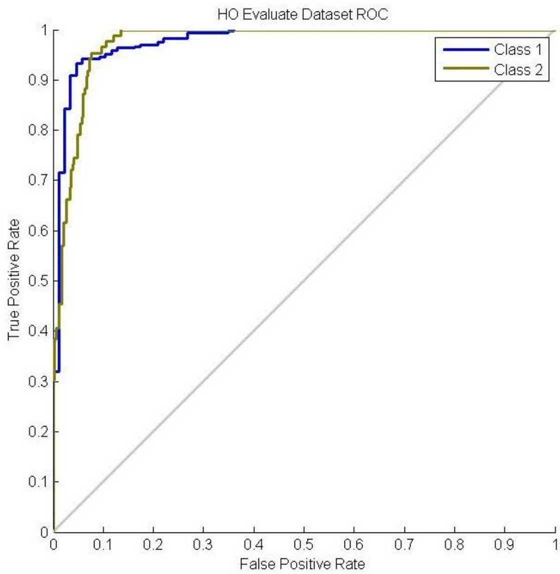

Figure 6-39: ROC Plot for Evaluation of the SCG Training Algorithm with 171 Hidden Nodes

With regards to this architecture, it can be seen that in the evaluation phase, the trained PCNN system displayed good performance in all three algorithms. The architecture employing the RBP training algorithm performed the best among the three algorithms applied. The RBP training algorithm classifier achieved 98.3% accuracy in data classification, which differs by 0.3% from the results obtained by the classifier employing the LVM training algorithm in Section 6.3.3.1.

6.4 Summary

In this section, the simulation work that was undertaken in the research was presented. OPNET was used to evaluate the handover performance in the system and MATLAB was used to implement and evaluate the handover decision algorithm employing PCNN.

The benchmark for horizontal handover execution in the GSM-R system, as specified in [27], was 300 ms. It is expected that the handover delay for vertical handover would be considerably more due to the increased complexity of enabling inter-working between different access systems. With respect to handover management for the scenario investigated in this research study, the estimated total delay obtained through the OPNET simulation was 1.08 s. This is still significantly below the benchmark stated in [27], which stated that a service interruption of 10 s or more during handover was unacceptable in a rail environment. Moreover, the simulation demonstrated the stability of the proposed handover scheme in handling the "ping pong" (i.e. due to the fluctuation of the satellite signal strength) effect of conventional handover algorithms. This is expected since a location-aided handover strategy was developed to provide stability of the handover algorithm. As such, the algorithm does not depend entirely on the measurements of the signal strength.

Moreover, buffers could be implemented to optimise the handover process and could be implemented at the T-IWU in the train and also at the ER of the Internet Service Provider. This is to prevent packet losses during the handover process. From the simulation results, it can be concluded that the buffer should be designed to sustain a 3.5 s interruption during the handover process. In order to manage the queue more efficiently during handover, a queue management system, such as Weighted Fair Queuing or Priority Queuing, can also be implemented to optimise the network operation and prevent traffic congestion.

Another observation noted was that handover procedure could be deterred if the length of the tunnel/train station is shorter than the length of the train (i.e. train length is about 300 m), then antenna diversity can be implemented instead of handover since certain parts of the train are still under the coverage area of the satellite. In such cases, a switch can be implemented to swap between the different antennas. However, a more sophisticated algorithm may be required to decide on the best methodology.

On the other hand, a train's journey is predictive and similar most of the time, which makes it worthwhile to explore if PCNN could be adopted as a HD algorithm and adapted for use in location-aided ISHO between the different access segments. The simulation of the three different PCNN architectures with respect to the three training algorithms, LVM, RBP and SCG, were simulated in MATLAB.

The performance results exhibited from the MATLAB simulation demonstrates the suitability of the proposed approach. The MATLAB simulation results achieved in the training, validation and testing phase showed that the determination of the appropriate number of hidden nodes for the respective training algorithm is related to achieving good generalisation behaviour of the PCNN system for handover. This is because complexity of the PCNN system is related to the increased number of hidden nodes. An example of allocating inappropriate number of hidden nodes was observed in the PCNN classfier architecture with 76 hidden nodes employing the SCG algorithm. It was noted that underfitting occurred, which was reflected in the classifier's poor performance to generalise the samples for the training, validation and testing phase. This was also corroborated in the classifier's performance during the evaluation phase.

The confusion matrix, see Figure 6-12, showed that the PCNN system with 76 hidden nodes and adopting the LVM training algorithm provided the best performance in training, validation and testing compared to the other PCNN architecture for handover. This is further confirmed by the simulation results achieved in the evaluation phase, as shown in Figure 6-22 and Figure 6-23, when Dataset 2 was applied to the trained classifier. It showed that the classifier was able to effectively generalise almost 99% of the data samples and illustrates that PCNN shows potential as a handover decision algorithm and is able to provide accuracies that is comparable to the benchmark of 99.5% specified in the GSM-R specification [27].

On another note, if the complexity of the system increases and if the training duration needs to be optimised, then SCG and RBP are fast efficient alternative training algorithms that can be employed. The results from the evaluation phase showed that, with the appropriate number of hidden nodes adopted, when the PCNN system employs the SCG or RBP training algorithm, it would still yield good generalisation behaviour of about 94%. This is taking into account that the PCNN system might not have achieved a significantly good performance during the training, testing and validation phase.

7 CONCLUSIONS AND FURTHER WORK

7.1 Conclusions

Over the last two decades, significant research developments into heterogeneous networking have been widely explored, as shown in [122] and [123]. With the increasing demand by consumers to have Internet access at any time and place it is foreseeable that enabling of heterogeneity between different access technologies will remain an important aspect to be addressed for future generations of wireless communication, as can be seen in the Information and Communication Technologies work programme of the H2020 programme [124].

Moreover, as stated in [125], it is foreseeable that GSM-R would be deemed obsolete around 2030 and work is currently undergoing by the European Railway Agency (ERA) in identifying a successor to the GSM-R system. The work undertaken in this research, have shown the potential of adopting a hybrid satellite and terrestrial network for supporting Internet access in a high-speed train environment, through using gap filler technologies, such as WiFi, to extend the satellite coverage to the train. This is attuned to the findings that are addressed in [125], especially in relation to the consideration of heterogeneous networking between multi-technology networks, such as GSM-R, WiFi, LTE and satellite systems.

Taking into account from the perspective of the network, the train is a subnet roaming within the Internet Service Provider’s subnet; therefore network layer handover would not be required. However, for the different access technologies to work harmoniously, specific functional models, signalling protocols and message formats for mobility management were defined, based on the approaches specified in the MONET methodology, ITU-T Q.65 UFM and ITU-T Q.1711 IMT-2000 FM, which was then simulated in OPNET. The results from OPNET illustrated that:

- The proposed handover scheme was capable of handling the “ping pong” effect of conventional handover algorithm, and
- An approximate total handover delay of 1.08s is expected, and buffers could be implemented to optimise the handover process.
- Alternatively, antenna diversity employing an appropriate algorithm could be implemented to obviate the need for handover in certain scenarios.

To optimise the handover process, a novel approach of employing PCNN as a HD algorithm was investigated in this research study through MATLAB simulations. It was observed that:

- The classifier consisting of 76 hidden nodes and employing the LVM algorithm was able to effectively generalise 99% of the data samples in Dataset 1 during the training, validation and testing phase.
- This was further corroborated by the performance of about 99% that was achieved by the trained classifier when Dataset 2 was presented in the evaluation phase.

These results from both phases effectively depicts the accuracies performances achieved by the PCNN classifier is close to conforming to the 99.5% benchmark for GSM-R that is stated in [27] and validates that the classifier shows great potential to be adopted as an intelligent HD algorithm compared to conventional algorithms.

7.2 Summary of Chapter Achievements

The main outcomes from this thesis are summarised as follows:

- In chapter 2 and 3, the basic fundamentals required to complete this research was discussed. Chapter 2 provided a literature review of current state-of-the art technologies, inclusive of a background of mobile networks, W-LAN, heterogeneous networking and IP. The background of mobility management, focusing on handover management and the procedures, was covered in chapter 3.
- In chapter 4, the adopted system scenario and specification requirements for HO were addressed. The design methodology for handover was identified, which would be relevant to how the functional model and the vertical handover signalling protocols are developed. The MONET methodology was largely based on conventional handover procedures that mainly considers RSS during handover. In this research study, the methodology was adapted to support location-aided handover, which included defining new functional entities, such as LDF, and the signalling protocols. The functional models, signalling protocols and architecture that is presented in this chapter is correlated to the OPNET simulation for this research.
- In chapter 5, a novel intelligent HD algorithm was proposed that exploits the use of PCNN. This was chose due to the train's journey remaining perpetually unchanged, and the prospects that patterns could be identified in handover that could facilitate the handover process. The accuracy benchmark of 99.5%, from [27], was employed as a

performance target to be achieved by the algorithm. To determine the optimal learning algorithm that was suitable for the PCNN classifier and still be able to generalise and learn, the three training algorithms LVM, RBP and SCG was investigated. It was observed that to achieve a comparable performance for each training algorithm, the number of hidden nodes defined in the classifier would differ. Therefore, three classifier architectures, consisting of 76, 86 and 171 hidden nodes, was determined and modelled in MATLAB.

- In this chapter 6, the simulation activities consists of modelling the proposed functional model and signalling protocols from chapter 4 in OPNET, and the PCNN HD algorithm from chapter 5 in MATLAB. The results that were achieved in the simulations were analysed and evaluated. The modelling in the OPNET simulation validated the numerical calculations that a total handover delay of approximately 1.08 s was expected. From the training, validation, testing and evaluation results in MATLAB, the accuracy performance of 99% achieved by the classifier affirms the suitability of adopting pattern classification as a handover decision algorithm for this research.

7.3 Future Work

This research is akin to the work that has been addressed by the transport theme stated in the European Commission for Research & Innovation [126]. The concept that is introduced in this research is transferable to other vehicular environments and is an approach that can be adapted for providing Internet access to high-speed trains. The designed handover algorithm, which used geographical location information, can also be adopted in predictive vertical handover schemes for homogeneous or heterogeneous networks. There is ample scope for extending the work on the handover management procedures that have been specified and achieved in this work; one approach is by adapting the current system to incorporate other mobile and wireless technologies, such as the 3GPP LTE/EPC system and IEEE 802.16m WiMAX system. The architecture and design methodology are then required to take into account the additional protocols of both technologies before evaluating the performance of the system. It is also foreseeable that the system can be further optimised by adopting the work that has been addressed in IEEE 802.21 into the system architecture.

Moreover, a limitation of the algorithm was that the pattern classification NN was trained based on a fixed data set. The performance of the algorithm can be further enhanced by incorporating fuzzy logic reasoning to achieve a hybrid intelligent system that is capable of further improving the behaviour of the algorithm. For example, in [127], the adoption of a fuzzy-logic concept for HI was proposed. The approach takes into consideration criteria such as the BER, network coverage, QoS and RSS of the different access technologies in the algorithm for determining HI. The technique that was employed can be integrated with the adopted NN in this work to improve the performance of the handover decision algorithm. Alternatively, other NN systems, such as Radial Basis Function (RBF) or Kohonen’s SOM neural networks [128], could also be investigated for vertical handover in heterogeneous networking. In [129], the adoption of SOM NN for LTE femtocells was addressed. The work investigates the adoption of SOM to optimise the handover of mobile subscribers, which can be transferable for handover approaches in a VE.

Another proposed future research direction that can be undertaken is to further explore the possibility of engaging artificial cognitive system for heterogeneous networking in VE. The work undertaken in this research can be used as a basis to further develop a cognitive system that can enhance the *modus operandi* of a railway network. For example, the day to day fleet management of the trains. The adoption of cognitive system is in line with the future and emerging technologies theme listed in the H2020 vision that will be addressed in the upcoming EU Framework Programme 8 [130].

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APPENDIX A – WLAN-MT ARCHITECTURE

The W-LAN mobile terminal (WLAN-MT) was implemented by means of 802.11b WiFi commercial devices. A description of the overall architecture of the W-LAN MT and the functional description of its subsystems in view of the integration of the WLAN-MT into the system are discussed here. In this respect a key point is represented by the interface between WLAN-MT and T-IWU.

The WLAN-MT consists of three main segments, i.e. the Radio, Baseband (BB) and MAC controller. This is shown in Figure A- 1. The radio segment comprises a transmitter/receiver switch, amplifiers, a RF/IF converter and a quadrature modulator/demodulator. The BB segment is made up of Analogue-to-Digital converters (ADCs), de-spread/ spread functionalities and modulators for the spread spectrum technology. The MAC segment consists of PHY-MAC Interface, Serial Control Interface, Micro-programmed MAC engine, WEP (Wired Equivalent Privacy) controller, Memory Controller and Host Interface. Hence, the subsystems are elaborated below.

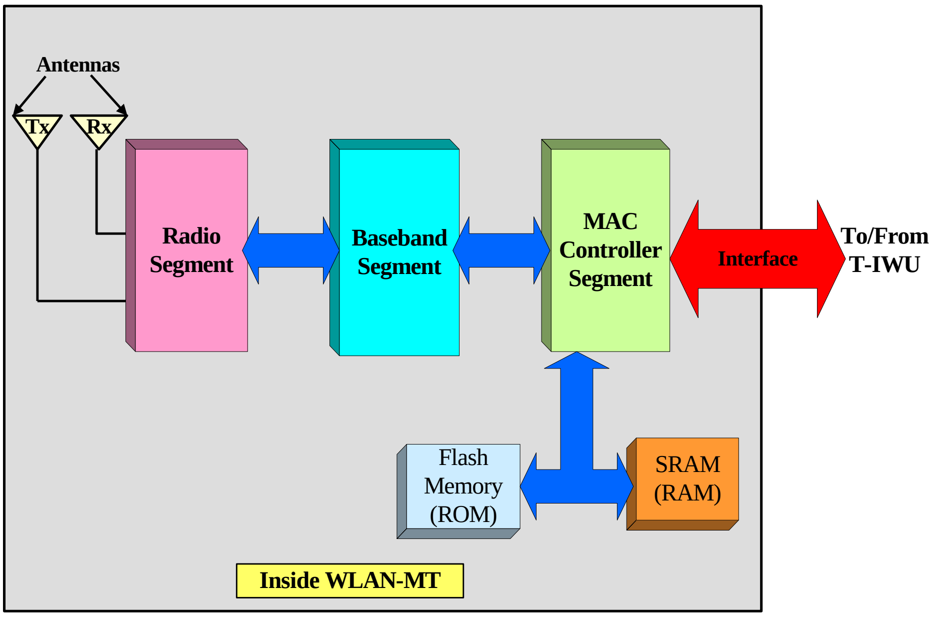

Figure A- 1: WLAN-MT General Architecture

Radio Segment

The radio subsystem architecture is shown in Figure A- 2 indicating the path travelled by the received and transmitted signal and the different components involved.

The Tx/Rx (Transmitter/Receiver) switch functionality is to switch according to whether the signal is to be transmitted or received. The RF/IF Converter for the receiving signal path, down converts the RF frequency to the Intermediate Frequency (IF) frequency. That is based on [131], it converts from 2.4 GHz ISM band to the IF centre frequency of 280 MHz. For the transmitting signal path, the RF/IF converter then performs the up conversion of the IF frequency to the RF frequency. The quadrature modulator functionalities are to perform quadrature modulation and demodulation of the IF signal into “I” and “Q” signals or vice versa. For the receiving signal path, the quadrature modulator then outputs three kinds of signal; RSSI (Received Signal Strength Indicator), I_{RX} (Received "I" Signal) and Q_{RX} (Received "Q" Signal). On the other hand, for the transmitting signal path, the quadrature modulator is responsible for modulating the I_{TX} and Q_{TX} signal and sends the output IF signal to the RF/IF Converter.

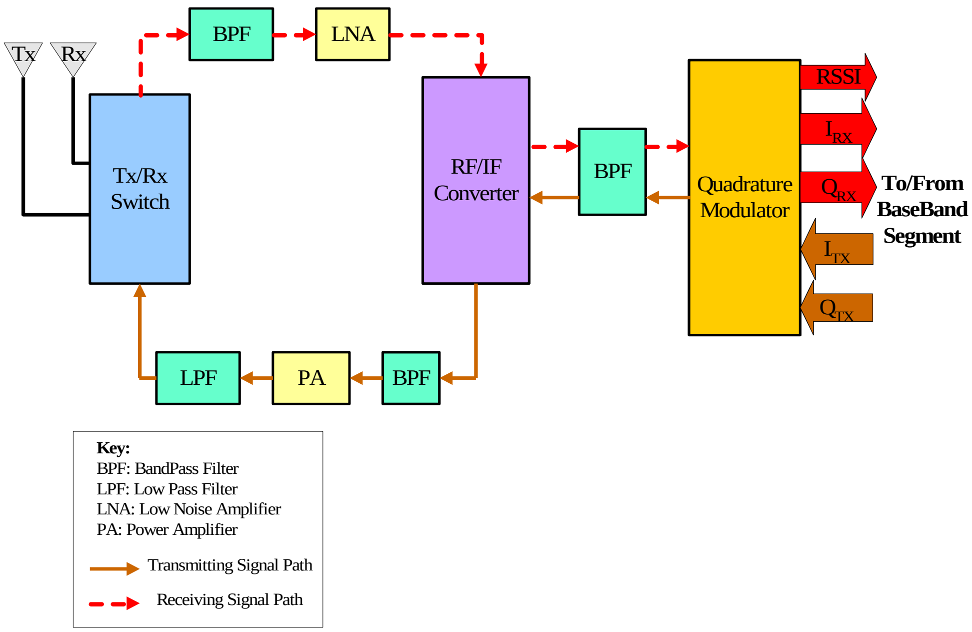

Figure A- 2: Radio Segment Architecture

Baseband Segment

The baseband segment of the WLAN-MT is illustrated in Figure A- 3. The BB segment communicates with the radio and MAC segments. Some manufacturers combine both the BB and MAC segment together. An example is Intersil ISL3873B - Wireless LAN Integrated MAC and Baseband Processor. However, the basic functionalities are similar and are discussed in this section.

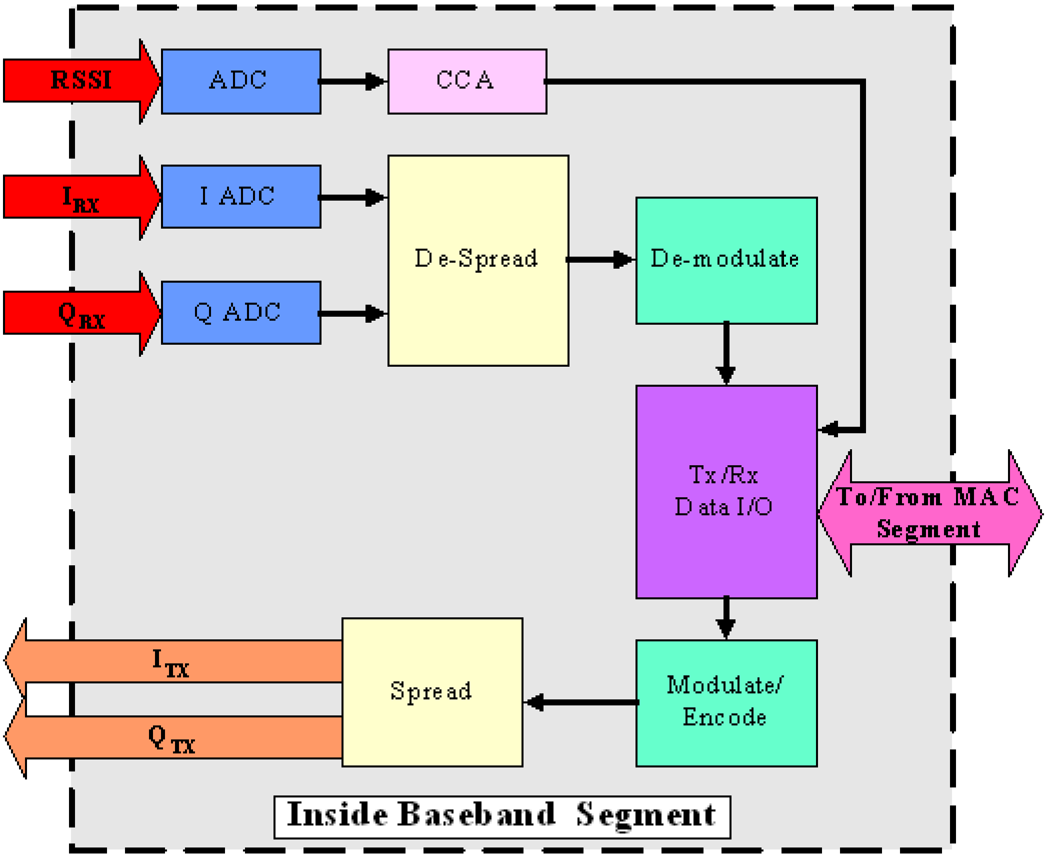

Figure A- 3: Baseband Segment Architecture

For the receiving signal path, the BB segment decodes and descrambles the DSSS "I" and "Q" data before forwarding it to the MAC segment. On the other hand, for the transmitting signal path, the BB segment scrambles, encodes and applies the spread spectrum modulation to the "I" and "Q" data before forwarding the DSSS data to the radio segment for transmission.

As shown in Figure A- 3, the Clear Channel Assessment (CCA) implements the carrier sense portion of the Carrier Sense Multiple Access (CSMA), as mentioned in [29]. Based on the RSSI, which indicates the energy at the antenna, the CCA functionality determines when the channel is clear to transmit [132]. Also stated in [132], the MAC decides on transmission based on traffic to send and the CCA indication. It is not compulsory for the MAC to utilise the CCA indication but it can enable the MAC to optimise the network throughput by minimising data collisions and reducing transmissions liable to errors.

Therefore, as mentioned before, the DSSS functionality is performed in the BB segment. The modulator performs the scrambling algorithm defined in [29], utilises Barker coding to generate the DBPSK (Differential Binary Phase Shift Keying), DQPSK (Differential Quadrature Phase Shift Keying) and CCK spread spectrum “I” and “Q” signals. As IEEE 802.11b supports 1 Mbps, 2 Mbps, 5.5 Mbps and 11 Mbps, there are different spread spectrum signals, further detailed description can be found in [133]. The reverse occurs for the demodulator, it removes the carrier frequency offset from the DSSS received “I” and “Q” signals, decodes and descrambles the data and forwards it. The Barker Code is the only spreading code that has been approved by the IEEE 802.11.

The Tx/Rx Data I/O (Transmit/Receive Data Input/Output) forwards/receives the MPDU (MAC Protocol Data Unit) Data to/from the PHY Interface and also communicates with the Modem Management Interface (MMI) in the MAC controller, to program the registers and functionality of the PHY BB processor.

Medium Access Control (MAC) Segment

The MAC segment implements the CSMA/CA for the access to the wireless medium, and is used to provide error control, synchronisation between the physically connected device and the communication channel and is responsible for prioritising and allocating access to the channel. The main functionalities of the MAC segment are based on the IEEE 802.11 and

802.11b standards, a detailed explanation of which can be found in [29] and [31]. Therefore, only a brief explanation is provided in this section.

The MAC segment utilises external SRAM and Flash Memory for code and data storage space. The maximum possible memory space is 4 Mbytes, but if the host interface is USB (Universal Serial Bus) then the memory space is reduced to 1 Mbyte. The external SRAM and Flash Memory use most of the storage space to store received and transmitted data. Figure A- 4 shows the external storage devices and MAC architecture.

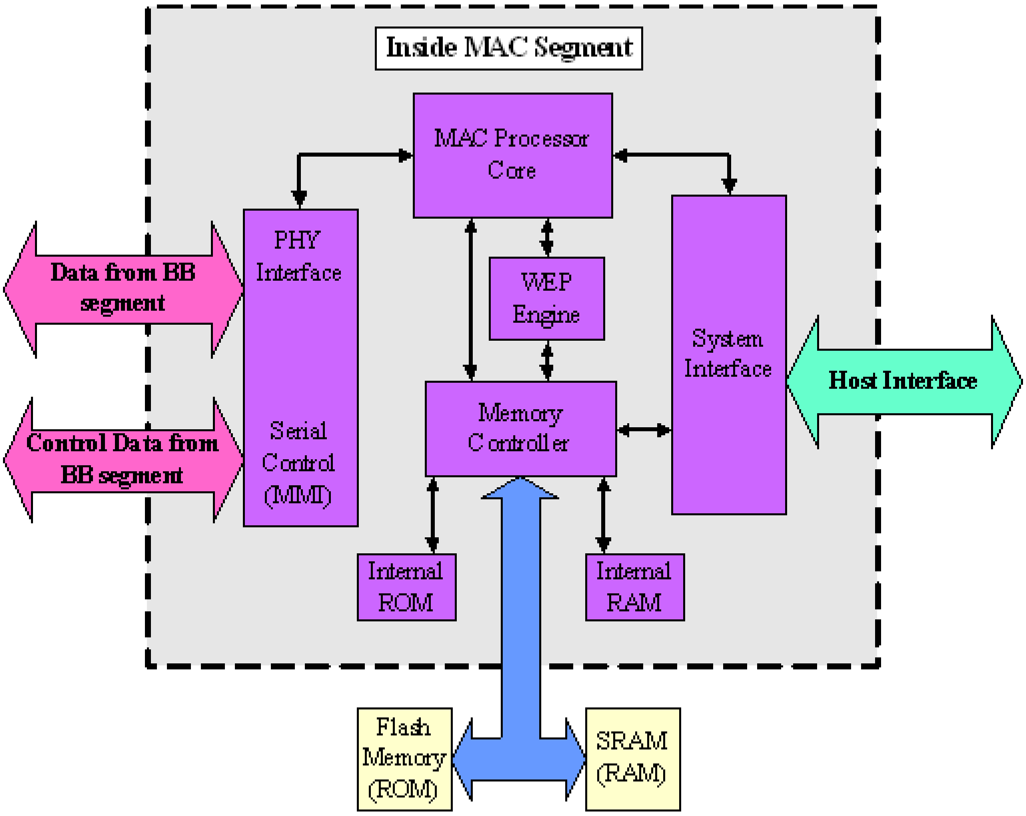

Figure A- 4: Medium Access Control (MAC) Segment Architecture

As mentioned previously, the PHY Interface is used to receive and transmit the MPDU data. While the Serial Control Port (MMI) is used to read and write internal registers in the baseband processor and access per-packet

PLCP (Physical Layer Convergence Protocol) information to provide CCA and carrier sense [134].

In [31], the authentication procedures consider two kinds of authentication services, which are the Open System Authentication and Shared Key authentication. The Shared Key authentication is only feasible if the WEP option is implemented, which is performed by the WEP engine as shown in Figure A- 4. The WEP algorithm is described in [31] and will not be further discussed in this document. The MAC Processor Core implements the IEEE 802.11 MAC Protocol for the MAC layer and is further elaborated in [31]. The Host Interface is the interface between the W-LAN Mobile Terminal and the T-IWU interface, as stated before.

Interface between WLAN-MT and T-IWU

There are several kinds of WiFi client adapter that are currently available that can be implemented as the WLAN-MT, i.e. PCI (Peripheral Component Interconnect) wireless LAN cards, Compact Flash wireless LAN cards, CardBus wireless LAN adapters, PC (Personal Computers) card wireless LAN adapters and USB W-LAN adapters. They differ in the interface when connecting to the T-IWU. Therefore, a brief description of the different interfaces supported by the W-LAN adapters is presented and the suitable interface proposed for the system between the T-IWU and WLAN-MT will be provided.

Peripheral Component Interconnect (PCI) Wireless LAN Card

The W-LAN PCI card is installed in PCI-equipped equipment, such as desktop PC and is compatible with most operating systems. The host device (e.g. desktop PC) is required to have available PCI slots. Different manufacturers support different WEP encryptions; some support both 64- or 128-bit WEP encryptions, while others might only support 128-bit WEP encryption. Based on GEMTEK WL-360 Datasheet [135], the W-LAN PCI adapter host interface is the PCMCIA PCI Card Prism 2.5 and is able to support a frequency range of 2.4 GHz to 2.4835 GHz ISM bandwidth. It has an operating range of 100 m to 300 m in open environment and 30 m to 100 m in indoor environment. More information on W-LAN PCI client adapters can be found in [135], [136] and [137]. The 3Com 802.11b W-LAN PCI adapter and Gemtel WL-360 Series W-LAN PCI adapter are shown in Figure A- 5.

Figure A- 5: Example of Wireless LAN PCI Adapters

Compact Flash (CF) Wireless LAN Card

The Compact Flash (CF) W-LAN card is used for PDA (Personal Digital Assistant) and handheld PC devices to provide connectivity to the W-LAN for mobile users. To use this W-LAN client adapter, the host should be a Compact Flash Type I or II interface. This type of interface is found in most PDA and handheld PC devices. Similar to the PCI W-LAN Card, different manufacturers support different WEP encryption. For example, GEMTEK WL-379F W-LAN CF card supports 64- and 128-bit WEP encryption, NETGEAR 802.11b W-LAN CF Card supports 40-, 64- and 128-bit WEP encryption and SOCKET W-LAN CF Card support 40- and 128-bit WEP encryption. The GEMTEK WL-379F [138] host interface is Compact Flash Type II. It is able to support a frequency range similar to the GEMTEK WL-360 [135], subject to local regulations, and in open areas the operating range is up to 250 m and in indoor environment it is about 60 m. More information regarding this type of CF W-LAN card is stated in [138], [139] and [140]. Figure A-6 shows the three W-LAN CF card examples listed.

Figure A- 6: Example of Compact Flash (CF) W-LAN Cards

Personal Computer (PC) Card Wireless LAN Adapters

There are two kinds of PC Card W-LAN adapters available and approved by PCMCIA (Personal Computer Memory Card International Association). The two kinds are 16-bit and 32-bit I/O PC card interfaces. The 32-bit I/O PC card technology is usually identified by the term “Cardbus Adapter”. PCMCIA also defines the physical specification of the three kinds of PC card as Type I, II or III. The three types differ only in the thickness of the card.

The more common sizes for the PC card W-LAN adapters are Type I and II. A Type I PC card can be inserted into a PCMCIA Type I or Type II 16- or 32-bit slot but a Type II PC card can be inserted into a PCMCIA Type II or Type III 16- or 32-bit slot but not a PCMCIA Type I slot. These PC card W-LAN adapters are usually slotted into laptops, PDA or devices (such as a desktop PC) that have a PCMCIA to PCI adapter. The 16-bit PC card and Cardbus adapters functionality are presented below.

- 16-bit W-LAN PC Card

  With reference to the GEMTEK WL-711 Datasheet [141], the host's slot size is a PCMCIA Type II and the host interface is PCMCIA PC Card to Computer. It allows 64- and 128-bit WEP encryption and the frequency range is 2.4 GHz to 2.4835 GHz ISM bandwidth. In open areas, it is able to provide a coverage area of 100-300 m and in indoor environment a coverage area of 30-100 m. Figure A - 7 shows the GEMTEK WL-711 W-LAN PCMCIA and 3Com 11Mbps W-LAN PC Card with Xjack ® Antenna.

Figure A- 7: Example of 16-bit W-LAN Personal Computer (PC) Card

• 32-bit W-LAN Cardbus Adapter

There are a number of manufacturers that produce 32-bit cardbus adapters for multi-mode W-LAN, such as GEMTEK WL-611G 802.11b/g Dual Mode Cardbus Adapter or 3Com 11a/b/g Wireless PC Card with XJACK® Antenna. However, there are also 32-bit 802.11b W-LAN cardbus adapters such as D-Link AirPlus DWL-650+ Wireless LAN CardBus PC Card. Figure A- 8 shows these various cardbus adapters. Based on the GEMTEK WL-611G Datasheet [142], this device supports 64- or 128-bit WEP encryption and the operating range is 2.412 GHz to 2.497 GHz. It is a dual mode Cardbus W-LAN adapter, that is it can be used for both IEEE 802.11b and IEEE 802.11g W-LAN. The operating range performance for IEEE 802.11b mode is 11 Mbps for up to 180 m, and for indoor environment, at 11 Mbps up to 60 m. The supported channels for 802.11b are similar to the other W-LAN client adapters mentioned before. Different manufacturers produce different Cardbus W-LAN adapters and the WEP encryption varies from one Cardbus W-LAN adapter to another. However, the common available WEP encryption bits are 40-, 64-, 128-, 154- or 256-bit.

Figure A- 8: Example of 32-bit CardBus W-LAN Adapter

For 16-bit and 32-bit PC Card W-LAN adapters, both require the host device to either have PCMCIA Type I, II or III slots to install the device. Therefore, if this type of interface is chosen, the device is expected to have a PCMCIA Type I, II or III slot or a PCMCIA to PCI adapter can be used. The antenna of these devices is usually installed in the card itself or attached to the card.

Universal Serial Bus (USB) Wireless LAN Adapter

To utilise the USB W-LAN adapter, the host device (e.g. T-IWU, PC desktop or Laptop) should have a USB Port. A USB cable is then used to connect the USB W-LAN adapter to the host device. The cable is usually a USB Type A connector on one end and the other is a USB Type B connector. This is an external W-LAN adapter and can be placed at any desired location (e.g. on the roof or wall of the train). Similar to other client adapters listed before, different manufacturers support different WEP encryption and the common supported bits are 40-, 64-, 128-bit WEP encryption. For example, Netgear MA101 2.4GHz 11 Mbps USB Adapter supports 40-, 64- and 128-bit WEP encryption, GEMTEK WL-780 W-LAN USB device supports 64 and 128-bit WEP encryption. If based on the GEMTEK WL-780 Datasheet [143], the host interface to the T-IWU would be USB Type A and to the USB adapter would be USB Type B. The operating range for outdoor environment would be 100 m to 300 m and for indoor environment is 30 m to 100 m. Figure A- 9 shows some examples of USB W-LAN adapters.

Figure A- 9: Example of Universal Serial Bus (USB) W-LAN Adapter

Proposed T-IWU and WLAN-MT Interface

Table A- 1 provides a brief summary of the available W-LAN adapters that could be implemented as the suitable WLAN-MT. It can be seen that the most optimum choice for the WLAN-MT was to utilise a USB type of W-LAN adapter. The T-IWU and WLAN-MT physical interfaces are based on the Universal Serial Bus 1.1 (USB 1.1) [144]. Based on [144], the host is the T-IWU and the physical device is the WLAN-MT. This implies that the T-IWU should support the USB technology and is made up of three layers: the function layer (i.e. Client Software); USB device layer (i.e. USB system Software); and the USB bus layer (i.e. the USB host controller). As the T-IWU is the host, it should be the root hub of the USB system that allows USB physical devices or other external hubs to be attached to it. The WLAN-MT is the physical device and also consists of the same three layers: the function layer (i.e. Device function); USB device layer (i.e. USB logical device); and USB bus interface layer (i.e. USB bus interface). The T-IWU should be able to support the signalling listed in [144], such as RESET, SUSPEND, RESUME and EOP (End-of-Packet) signalling. The USB protocol consists of four basic types of data transfer, i.e. Control Transfer, Bulk Transfer, Interrupt Data Transfer and Isochronous Data Transfer. Therefore, the T-IWU and WLAN-MT should be able to support Bulk, Interrupt, Control and Isochronous Transactions. The T-IWU should also be able to send “IN”/“OUT” tokens, handshake packets such as “ACK” “NAK” “STALL” and receive data and handshake packets for the transactions process. The WLAN-MT should be able to receive “IN”/”OUT” tokens and send handshake packets for the transactions process. A detailed description is available in [144]. Figure A- 10 describes the communication from the point of view of the host and its layers and Figure A- 11 shows the protocol stack for the WLAN-MT using the USB interface. Even though the work performed here was based on the previous USB 1.1 specification, the baseline host communication and protocol layer that was stated in the revised specification [145] remained the same and therefore should not affect the protocol stack that was defined for the system.

Type of W-LAN Adapters	Summary	Suitability
PCI	• Used for PCI-equipped equipments, i.e. desktop PC. • Requires T-IWU to have PCI slots. • It is an internal device, therefore is installed within T-IWU.	• Installed within T-IWU, adapter position not flexible. • T-IWU needs to shut down to remove or install the adapter. • Depending on the position of the T-IWU, the MT may registers with the AP in the Internal LAN • Not really suitable for WLAN-MT implementation unless T-IWU is not positioned within the AP of the train.
Compact Flash	• Used in handheld PC devices and PDA. • Requires T-IWU to have a Compact Flash Type I or II interface. • It is a "plug and play" device and is installed within T-IWU.	• Installed within T-IWU, adapter position not flexible. • It is a "plug and play" device, hence might not need to shut down T-IWU. • Depending on the position of the T-IWU, the MT may register with the AP in the Internal LAN • Requires Compact Flash Type I or II interface and requires T-IWU to have this interface, which is usually found in PDA or handheld devices. • Not really suitable for WLAN-MT implementation unless T-IWU is not positioned within the AP train and that T-IWU supports compact Flash Type I or II interface.
PC Card	• Used in laptops, PDA or devices that have PCMCIA to PCI adapter (e.g. desktop PC). • Requires T-IWU to have a PCMCIA Type I or II or III slot. • It is a "plug and play" device and is installed within T-IWU.	• Installed within T-IWU, adapter position not flexible. Even if a PCMCIA to PCI adapter is used, it has to be placed into PCI slot. • If 16-bit PC card, requires a 16-bit connector and 32-bit cardbus require 32-bit connector. • It is a "plug and play" device, hence might not need to shut down T-IWU. • If T-IWU position within train might register to indoor W-LAN. • Not really suitable for WLAN-MT implementation unless T-IWU is not positioned within the AP of the train and that T-IWU supports PCMCIA Type I or II or III slot or uses PCMCIA to PCI adapter.

Type of W-LAN Adapters	Summary	Suitability
USB	• Used by devices that support USB. (E.g. PC or Laptop that has a USB port.) • Requires T-IWU to support USB and have a USB port. • It is a "plug and play" device and can be connected by a USB cable. It is an external device.	• Connected to USB port or can be connected to T-IWU by a USB cable. Is an external device, so adapter positioning is flexible. • Is a "plug and play" device, so no need to shut down to remove adapter. • If T-IWU position within train, the USB cable can be use to extended up to a maximum of 5 m for high-speed devices (due to propagation of electromagnetic fields). • For a distance of more than 5 m, a USB repeater cable can be used. • Device if placed external to the train coverage, prevents registering to indoor W-LAN. • Suitable to be implemented as WLAN-MT, as USB port is easily available and T-IWU can be positioned in the train.

Table A- 1: Summary of W-LAN Adapters

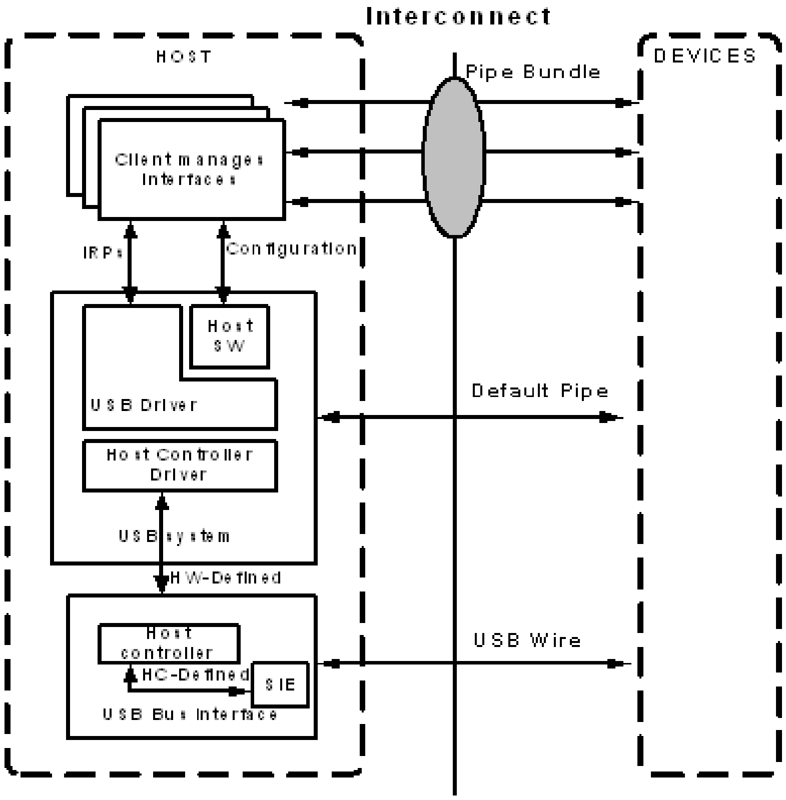

Figure A- 10: Host (e.g. T-IWU) Communications

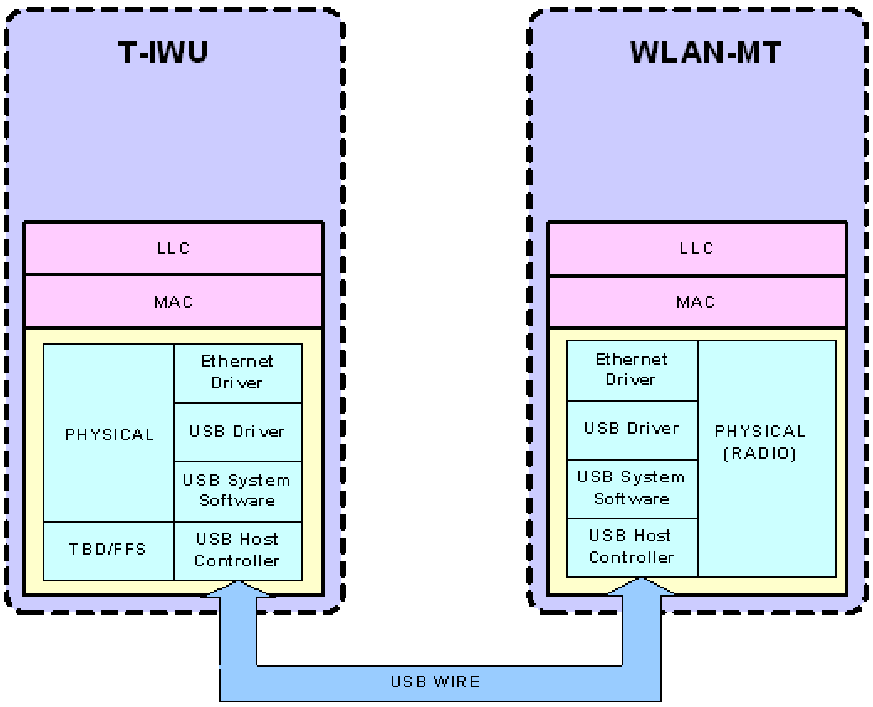

Figure A- 11: Protocol Stack for WLAN-MT using USB interface

APPENDIX B – MESSAGE FORMAT

r_a: LDF – SHRM

This message is sent by LDF to SHRM periodically and no response is required. The location information is used by SHRM to evaluate if a forced handover should be initiated.

LDF.RPT		
ITEM	req.ind	resp.conf
FA_ID[3]	Mandatory	-
Position of MT	Mandatory	-
Timestamp	Optional	-
Seg ID	Mandatory	-

Table B- 1: LDF.RPT Message Format

r_b: SHRM – HI

This message is sent to HI to request for a forced handover. This is based on location information provided by LDF.

SPEC.HO.REQ.MT		
ITEM	req.ind	resp.conf
FA_ID	Mandatory	Mandatory

[3] FA_ID (FIFTH Association ID)- This is similar to the AID used in [92] and the Association ID used in [83]. It is called FA_ID to avoid confusion with the term AID used in W-LAN association, reassociation and disassociation procedures.

Originator ID	Mandatory	-
New Seg ID	Optional	-
Old Seg ID	Optional	-
New Element ID	Optional	-
MT Record Data	Optional	-
Urgency Class	Optional	-
Result Indicator	-	Mandatory

Table B- 2: SPEC.HO.REQ.MT Message Format

r_c: LUH – HI

In the handover initiation phase, LUH should send this message to HI periodically. The message notifies HI of which access segment or segments are currently available.

LUH.RPT		
ITEM	req.ind	resp.conf
FA_ID	Mandatory	-
Segment Availability List	Mandatory	-

Table B- 3: LUH.RPT Message Format

r_d: TCCM – HI

A CAND.LIST.RPT message is sent periodically to HI from each access segment and no response is required. HI then processes the messages sent from each access segment.

CAND.LIST.RPT		
ITEM	req.ind	resp.conf
FA_ID	Mandatory	-
Seg ID	Mandatory	-
Element ID	Optional	-
Signal Strength	Mandatory	-
Delay	Optional	-
Bandwidth Availability	Optional	-

Table B- 4: CAND.LIST.RPT Message Format

r_e: HMPM – HI

This message provides information regarding the MT preferences to HI.

MT. DATA		
ITEM	req.ind	resp.conf
FA_ID	Mandatory	Mandatory
MT Record Type	Mandatory	-
MT Record Data	-	Mandatory
Result Indicator	-	Mandatory

Table B- 5: MT.DATA Message Format

r_f: HI – HD

In [92], two messages were considered one being HANDOVER_INTI_REQ and the other SPEC_HO_REQ. The SPEC_HO_REQ message is not considered in the system as the forced handover message originates from the network and, as the MT is in control of the handover. Therefore HO.EXE.RQ message is sent from HI to HD to request for handover and proceeds with the Decision phase.

HO.EXE.REQ		
ITEM	req.ind	resp.conf
FA_ID	Mandatory	Mandatory
Originator ID	Mandatory	-
New Seg ID	Optional	-
Old Seg ID	Optional	-
New Element ID	Optional	-
Old Element ID	Optional	-
New Channel ID	Optional	-
Bearer Class	Optional	-
QoS Class	Optional	-
Security Class	Optional	-
Urgency Class	Optional	-
Max Delay	Optional	-

Type of HO	Optional	Optional
HO Reason	Optional	-
Seg Availability Record	Optional	-
Signal Strength Measurement	Optional	-
HO Estimated Duration	Optional	-
Position of MT Threshold	Optional	-
Delay Threshold	Optional	-
Signal Strength Threshold	Optional	-
Result Indicator	-	Mandatory

Table B- 6: HO.EXE.REQ Message Format

r_g: LDF – HI

This message is sent by LDF to HI periodically and no response is required.

This message provides the geographic positioning of the MT to HI.

LDF.RPT		
ITEM	req.ind	Resp.conf
FA_ID	Mandatory	-
Seg ID	Mandatory	-
Position of MT	Mandatory	-
Timestamp	Optional	-

Table B- 7: LDF.RPT Message Format

r_h: MEF – HI

This message provides a report of the link quality of the current link to HI periodically and no response is required.

LINK.QUAL.RPT		
ITEM	req.ind	Resp.conf
FA_ID	Mandatory	-
Seg ID	Mandatory	-
Element ID	Optional	-
BER	Optional	-
CIR	Optional	-
Signal Strength	Optional	-
Delay	Optional	-
Delay Jitter	Optional	-
Link Loss Probability	Optional	-
Time Before Link Loss	Optional	-

Table B- 8: LINK.QUAL.RPT Message Format

r_i: QIF – HI

This message provides a report of the overall QoS of the current link and is sent periodically. No response is required.

QIF.RPT		
ITEM	req.ind	resp.conf
FA_ID	Mandatory	-
Seg ID	Mandatory	-
Element ID	Optional	-
Packet Loss Ratio	Optional	-

Table B- 9: QIF.RPT Message Format

r_j: HCA – HC

This message is sent when requested by HC, and consists of the updated handover criteria. The criteria can be edited in HCA.

UPDATE.HO.CRIT		
ITEM	req.ind	resp.conf
FA_ID	Mandatory	Mandatory
BER Value	Optional	-
CIR Value	Optional	-
Signal Strength	Optional	-
Delay Value	Optional	-

Delay Jitter Value	Optional	-
Packet Loss Value	Optional	-
Position of MT Value	Optional	-
Result Indicator	-	Mandatory

Table B- 10: UPDATE.HO.CRIT Message Format

r_k: HC – HI

This message provides HI with the handover criteria, which is required by HI for the handover initiation process.

HO.CRITERIA		
ITEM	req.ind	resp.conf
FA_ID	Mandatory	Mandatory
BER ID	Optional	-
CIR ID	Optional	-
Signal Strength ID	Optional	-
Delay ID	Optional	-
Delay Jitter ID	Optional	-
Packet Loss ID	Optional	-
Position of MT ID	Optional	-
BER Threshold	-	Optional
CIR Threshold	-	Optional

Signal Strength Threshold	-	Optional
Delay Threshold	-	Optional
Delay Jitter Threshold	-	Optional
Packet Loss Threshold	-	Optional
Position of MT Threshold	-	Optional

Table B- 11: HO.CRITERIA Message Format

ŋ: HD – HOC

This message is sent to HOC to proceed with the handover execution phase. It implies that HD has completed the handover decision phase.

HO.EXE.CMD		
EM	req.ind	resp.conf
FA_ID	Mandatory	Mandatory
Originator ID	Mandatory	-
New Seg ID	Mandatory	-
Old Seg Id	Mandatory	-
New Element ID	Optional	-
Old Element ID	Optional	-
New Channel ID	Mandatory	-
Point of Attachment	Optional	-
Target Seg Record	Mandatory	-

New Service Provider ID	Optional	-
Bearer Class	Optional	-
QoS Class	Optional	-
Security Class	Optional	-
Urgency Class	Optional	-
Max Delay	Optional	-
Type of HO	Mandatory	-
Domain ID	Mandatory	-
Result Indicator	-	Mandatory

Table B- 12: HO.EXE.CMD Message Format

r_m: LUH – HD

HD sends the result of the handover decision phase to LUH.

HD.RESULT		
ITEM	req.ind	resp.conf
FA_ID	Mandatory	Mandatory
Seg ID	Mandatory	-
Result Indicator	-	Mandatory

Table B- 13: HD.RESULT Message Format

r_n: TCCN – HD

This message provides HD with information regarding the available resources in the targeted segment.

RESOURCE.INFO		
ITEM	req.ind	resp.conf
FA_ID	Mandatory	Mandatory
Target Seg Record	Mandatory	Mandatory

Table B- 14: RESOURCE.INFO Message Format

r_o: HMPN – HD

HD requests for service related information from HMPN. The information provided is related to the MT.

SERVICE.DATA		
ITEM	req.ind	resp.conf
FA_ID	Mandatory	Mandatory
MT Record Type	Mandatory	-
MT Record Data	-	Mandatory
Status	Optional	Mandatory
Result Indicator	-	Mandatory

Table B- 15: SERVICE.DATA Message Format

r_p / r_q: BC – HOC

This message consists of two types, one is for connection establishment and the other is to release the connection. Both messages consist of a request and response. The CONNECT message establishes the connection to the targeted segment and the RELEASE message releases the connection of the old segment.

CONNECT		
ITEM	Req.ind	resp.conf
FA_ID	Mandatory	Mandatory
New Seg ID	Mandatory	-
New Channel ID	Mandatory	-
Bearer Class	Optional	-
QoS Class	Optional	-
Security Class	Optional	-
Status	Optional	-
Result Indicator	-	Mandatory

Table B- 16: BC-HOC CONNECT Message Format

RELEASE		
ITEM	req.ind	resp.conf
FA_ID	Mandatory	Mandatory

Old Seg ID	Mandatory	-
Result Indicator	-	Mandatory

Table B- 17: BC-HOC RELEASE Message Format

r_S: SBC – HOC

The SWITCH.CONN message switches from one connection to another and upon completion a response is provided.

SWITCH.CONN		
ITEM	req.ind	resp.conf
FA_ID	Mandatory	Mandatory
Switch From ID	Mandatory	-
Switch To ID	Mandatory	-
Result Indicator	-	Mandatory

Table B- 18: SWITCH.CONN Message Format

APPENDIX C – PCNN DATASETS

The extracts of the datasets that are applied in the PCNN algorithm for the handover decision phase are listed in the following tables.

Inputs						Targetted Outputs	
Latitude	Longitude	SAT RSS	WLAN RSS	QoS	BW	SAT-Seg	WLAN-Seg
41.89	12.5	0.9	0.9	0.9	0.9	1	0
41.89	12.5	0.9	0.75	0.75	0.75	1	0
41.89	12.5	0.9	0.5	0.5	0.5	1	0
41.89	12.5	0.9	0.45	0.45	0.45	1	0
41.89	12.5	0.9	0	0	0	1	0
41.89	12.5	0.75	0.9	0.9	0.9	1	0
41.89	12.5	0.75	0.75	0.75	0.75	1	0
41.89	12.5	0.75	0.5	0.5	0.5	1	0
41.89	12.5	0.75	0.45	0.45	0.45	1	0
41.89	12.5	0.75	0	0	0	1	0
41.89	12.5	0.6	0.9	0.9	0.9	1	0
41.89	12.5	0.6	0.75	0.75	0.75	1	0
41.89	12.5	0.6	0.5	0.5	0.5	1	0
41.89	12.5	0.6	0.45	0.45	0.45	1	0
41.89	12.5	0.6	0	0	0	1	0
41.89	12.5	0.5	0.9	0.9	0.9	1	0
41.89	12.5	0.5	0.75	0.75	0.75	1	0
41.89	12.5	0.5	0.5	0.5	0.5	1	0
41.89	12.5	0.5	0.45	0.45	0.45	1	0
41.89	12.5	0.5	0	0	0	1	0
41.89	12.5	0.35	0.9	0.9	0.9	1	0
41.89	12.5	0.35	0.75	0.75	0.75	1	0
41.89	12.5	0.35	0.5	0.5	0.5	1	0
41.89	12.5	0.35	0.45	0.45	0.45	1	0
41.89	12.5	0.35	0	0	0	1	0
41.89	12.5	0.2	0.9	0.9	0.9	1	0
41.89	12.5	0.2	0.75	0.75	0.75	1	0
41.89	12.5	0.2	0.5	0.5	0.5	1	0
41.89	12.5	0.2	0.45	0.45	0.45	1	0
41.89	12.5	0.2	0	0	0	1	0
41.89	12.5	0	0.9	0.9	0.9	1	0
41.89	12.5	0	0.75	0.75	0.75	1	0
41.89	12.5	0	0.5	0.5	0.5	1	0
41.89	12.5	0	0.45	0.45	0.45	1	0
41.89	12.5	0	0	0	0	1	0
41.9049	12.4901	0.9	0.9	0.9	0.9	1	0
41.9049	12.4901	0.9	0.75	0.75	0.75	1	0

41.9049	12.4901	0.9	0.5	0.5	0.5	1	0
41.9049	12.4901	0.9	0.45	0.45	0.45	1	0
41.9049	12.4901	0.9	0	0	0	1	0
41.9049	12.4901	0.75	0.9	0.9	0.9	1	0
41.9049	12.4901	0.75	0.75	0.75	0.75	1	0
41.9049	12.4901	0.75	0.5	0.5	0.5	1	0
41.9049	12.4901	0.75	0.45	0.45	0.45	1	0
41.9049	12.4901	0.75	0	0	0	1	0
41.9049	12.4901	0.6	0.9	0.9	0.9	1	0
41.9049	12.4901	0.6	0.75	0.75	0.75	1	0
41.9049	12.4901	0.6	0.5	0.5	0.5	1	0
41.9049	12.4901	0.6	0.3	0.3	0.3	1	0
41.9049	12.4901	0.6	0	0	0	1	0
41.9049	12.4901	0.5	0.9	0.9	0.9	1	0
41.9049	12.4901	0.5	0.75	0.75	0.75	1	0
41.9049	12.4901	0.5	0.5	0.5	0.5	1	0
41.9049	12.4901	0.5	0.3	0.3	0.3	1	0
41.9049	12.4901	0.5	0	0	0	1	0
41.9049	12.4901	0.35	0.9	0.9	0.9	1	0
41.9049	12.4901	0.35	0.75	0.75	0.75	1	0
41.9049	12.4901	0.35	0.5	0.5	0.5	1	0
41.9049	12.4901	0.35	0.3	0.3	0.3	1	0
41.9049	12.4901	0.35	0	0	0	1	0
41.9049	12.4901	0.2	0.9	0.9	0.9	1	0
41.9049	12.4901	0.2	0.75	0.75	0.75	1	0
41.9049	12.4901	0.2	0.5	0.5	0.5	1	0
41.9049	12.4901	0.2	0.3	0.3	0.3	1	0
41.9049	12.4901	0.2	0	0	0	1	0
41.9049	12.4901	0	0.9	0.9	0.9	1	0
41.9049	12.4901	0	0.75	0.75	0.75	1	0
41.9049	12.4901	0	0.5	0.5	0.5	1	0
41.9049	12.4901	0	0.3	0.3	0.3	1	0
41.9049	12.4901	0	0	0	0	1	0
41.9149	12.4834	0.9	0.9	0.9	0.9	0	1
41.9149	12.4834	0.9	0.9	0.75	0.6	0	1
41.9149	12.4834	0.9	0.9	0.5	0.7	0	1
41.9149	12.4834	0.9	0.9	0.4	0.5	1	0
41.9149	12.4834	0.9	0.9	0	0	1	0
41.9149	12.4834	0.9	0.75	0.9	0.9	0	1
41.9149	12.4834	0.9	0.75	0.75	0.6	0	1
41.9149	12.4834	0.9	0.75	0.5	0.7	0	1
41.9149	12.4834	0.9	0.75	0.4	0.5	1	0
41.9149	12.4834	0.9	0.75	0	0	1	0
41.9149	12.4834	0.9	0.5	0.9	0.9	0	1
41.9149	12.4834	0.9	0.5	0.75	0.6	0	1
41.9149	12.4834	0.9	0.5	0.5	0.7	0	1

41.9149	12.4834	0.9	0.5	0.4	0.5	1	0
41.9149	12.4834	0.9	0.5	0	0	1	0
41.9149	12.4834	0.9	0.45	0.9	0.9	0	1
41.9149	12.4834	0.9	0.45	0.75	0.6	0	1
41.9149	12.4834	0.9	0.45	0.5	0.7	0	1
41.9149	12.4834	0.9	0.45	0.4	0.5	1	0
41.9149	12.4834	0.9	0.45	0	0	1	0
41.9149	12.4834	0.9	0	0.9	0.9	1	0
41.9149	12.4834	0.9	0	0.75	0.6	1	0
41.9149	12.4834	0.9	0	0.5	0.7	1	0
41.9149	12.4834	0.9	0	0.4	0.5	1	0
41.9149	12.4834	0.9	0	0	0	1	0
41.9149	12.4834	0.75	0.9	0.9	0.9	0	1
41.9149	12.4834	0.75	0.9	0.75	0.6	0	1
41.9149	12.4834	0.75	0.9	0.5	0.7	0	1
41.9149	12.4834	0.75	0.9	0.4	0.5	1	0
41.9149	12.4834	0.75	0.9	0	0	1	0
41.9149	12.4834	0.75	0.75	0.9	0.9	0	1
41.9149	12.4834	0.75	0.75	0.75	0.6	0	1
41.9149	12.4834	0.75	0.75	0.5	0.7	0	1
41.9149	12.4834	0.75	0.75	0.4	0.5	1	0
41.9149	12.4834	0.75	0.75	0	0	1	0
41.9149	12.4834	0.75	0.5	0.9	0.9	0	1
41.9149	12.4834	0.75	0.5	0.75	0.6	0	1
41.9149	12.4834	0.75	0.5	0.5	0.7	0	1
41.9149	12.4834	0.75	0.5	0.4	0.5	1	0
41.9149	12.4834	0.75	0.5	0	0	1	0
41.9149	12.4834	0.75	0.45	0.9	0.9	0	1
41.9149	12.4834	0.75	0.45	0.75	0.6	0	1
41.9149	12.4834	0.75	0.45	0.5	0.7	0	1
41.9149	12.4834	0.75	0.45	0.4	0.5	1	0
41.9149	12.4834	0.75	0.45	0	0	1	0
41.9149	12.4834	0.75	0	0.9	0.9	1	0
41.9149	12.4834	0.75	0	0.75	0.6	1	0
41.9149	12.4834	0.75	0	0.5	0.7	1	0
41.9149	12.4834	0.75	0	0.4	0.5	1	0
41.9149	12.4834	0.75	0	0	0	1	0
41.9149	12.4834	0.6	0.9	0.9	0.9	0	1
41.9149	12.4834	0.6	0.9	0.75	0.6	0	1
41.9149	12.4834	0.6	0.9	0.5	0.7	0	1
41.9149	12.4834	0.6	0.9	0.4	0.5	1	1
41.9149	12.4834	0.6	0.9	0	0	1	1
41.9149	12.4834	0.6	0.75	0.9	0.9	0	1
41.9149	12.4834	0.6	0.75	0.75	0.6	0	1
41.9149	12.4834	0.6	0.75	0.5	0.7	0	1
41.9149	12.4834	0.6	0.75	0.4	0.5	1	0

41.9149	12.4834	0.6	0.75	0	0	1	0
41.9149	12.4834	0.6	0.5	0.9	0.9	0	1
41.9149	12.4834	0.6	0.5	0.75	0.6	0	1
41.9149	12.4834	0.6	0.5	0.5	0.7	0	1
41.9149	12.4834	0.6	0.5	0.4	0.5	1	0
41.9149	12.4834	0.6	0.5	0	0	1	0
41.9149	12.4834	0.6	0.45	0.9	0.9	0	1
41.9149	12.4834	0.6	0.45	0.75	0.6	0	1
41.9149	12.4834	0.6	0.45	0.5	0.7	0	1
41.9149	12.4834	0.6	0.45	0.4	0.5	1	0
41.9149	12.4834	0.6	0.45	0	0	1	0
41.9149	12.4834	0.6	0	0.9	0.9	1	0
41.9149	12.4834	0.6	0	0.75	0.6	1	0
41.9149	12.4834	0.6	0	0.5	0.7	1	0
41.9149	12.4834	0.6	0	0.4	0.5	1	0
41.9149	12.4834	0.6	0	0	0	1	0
41.9149	12.4834	0.5	0.9	0.9	0.9	0	1
41.9149	12.4834	0.5	0.9	0.75	0.6	0	1
41.9149	12.4834	0.5	0.9	0.5	0.7	0	1
41.9149	12.4834	0.5	0.9	0.4	0.5	1	0
41.9149	12.4834	0.5	0.9	0	0	1	0
41.9149	12.4834	0.5	0.75	0.9	0.9	0	1
41.9149	12.4834	0.5	0.75	0.75	0.6	0	1
41.9149	12.4834	0.5	0.75	0.5	0.7	0	1
41.9149	12.4834	0.5	0.75	0.4	0.5	1	0
41.9149	12.4834	0.5	0.75	0	0	1	0
41.9149	12.4834	0.5	0.5	0.9	0.9	0	1
41.9149	12.4834	0.5	0.5	0.75	0.6	0	1
41.9149	12.4834	0.5	0.5	0.5	0.7	0	1
41.9149	12.4834	0.5	0.5	0.4	0.5	1	0
41.9149	12.4834	0.5	0.5	0	0	1	0
41.9149	12.4834	0.5	0.45	0.9	0.9	0	1
41.9149	12.4834	0.5	0.45	0.75	0.6	0	1
41.9149	12.4834	0.5	0.45	0.5	0.7	0	1
41.9149	12.4834	0.5	0.45	0.4	0.5	1	0
41.9149	12.4834	0.5	0.45	0	0	1	0
41.9149	12.4834	0.5	0	0.9	0.9	1	0
41.9149	12.4834	0.5	0	0.75	0.6	1	0
41.9149	12.4834	0.5	0	0.5	0.7	1	0
41.9149	12.4834	0.5	0	0.4	0.5	1	0
41.9149	12.4834	0.5	0	0	0	1	0
41.9149	12.4834	0.35	0.9	0.9	0.9	0	1
41.9149	12.4834	0.35	0.9	0.75	0.6	0	1
41.9149	12.4834	0.35	0.9	0.5	0.7	0	1
41.9149	12.4834	0.35	0.9	0.4	0.5	1	0
41.9149	12.4834	0.35	0.9	0	0	1	0

41.9149	12.4834	0.35	0.75	0.9	0.9	0	1
41.9149	12.4834	0.35	0.75	0.75	0.6	0	1
41.9149	12.4834	0.35	0.75	0.5	0.7	0	1
41.9149	12.4834	0.35	0.75	0.4	0.5	1	0
41.9149	12.4834	0.35	0.75	0	0	1	0
41.9149	12.4834	0.35	0.5	0.9	0.9	0	1
41.9149	12.4834	0.35	0.5	0.75	0.6	0	1
41.9149	12.4834	0.35	0.5	0.5	0.7	0	1
41.9149	12.4834	0.35	0.5	0.4	0.5	1	0
41.9149	12.4834	0.35	0.5	0	0	1	0
41.9149	12.4834	0.35	0.45	0.9	0.9	0	1
41.9149	12.4834	0.35	0.45	0.75	0.6	0	1
41.9149	12.4834	0.35	0.45	0.5	0.7	0	1
41.9149	12.4834	0.35	0.45	0.4	0.5	1	0
41.9149	12.4834	0.35	0.45	0	0	1	0
41.9149	12.4834	0.35	0	0.9	0.9	1	0
41.9149	12.4834	0.35	0	0.75	0.6	1	0
41.9149	12.4834	0.35	0	0.5	0.7	1	0
41.9149	12.4834	0.35	0	0.4	0.5	1	0
41.9149	12.4834	0.35	0	0	0	1	0
41.9149	12.4834	0.2	0.9	0.9	0.9	0	1
41.9149	12.4834	0.2	0.9	0.75	0.6	0	1
41.9149	12.4834	0.2	0.9	0.5	0.7	0	1
41.9149	12.4834	0.2	0.9	0.4	0.5	1	0
41.9149	12.4834	0.2	0.9	0	0	1	0
41.9149	12.4834	0.2	0.75	0.9	0.9	0	1
41.9149	12.4834	0.2	0.75	0.75	0.6	0	1
41.9149	12.4834	0.2	0.75	0.5	0.7	0	1
41.9149	12.4834	0.2	0.75	0.4	0.5	1	0
41.9149	12.4834	0.2	0.75	0	0	1	0
41.9149	12.4834	0.2	0.5	0.9	0.9	0	1
41.9149	12.4834	0.2	0.5	0.75	0.6	0	1
41.9149	12.4834	0.2	0.5	0.5	0.7	0	1
41.9149	12.4834	0.2	0.5	0.4	0.5	1	0
41.9149	12.4834	0.2	0.5	0	0	1	0
41.9149	12.4834	0.2	0.45	0.9	0.9	0	1
41.9149	12.4834	0.2	0.45	0.75	0.6	0	1
41.9149	12.4834	0.2	0.45	0.5	0.7	0	1
41.9149	12.4834	0.2	0.45	0.4	0.5	1	0
41.9149	12.4834	0.2	0.45	0	0	1	0
41.9149	12.4834	0.2	0	0.9	0.9	1	0
41.9149	12.4834	0.2	0	0.75	0.6	1	0
41.9149	12.4834	0.2	0	0.5	0.7	1	0
41.9149	12.4834	0.2	0	0.4	0.5	1	0
41.9149	12.4834	0.2	0	0	0	1	0
41.9149	12.4834	0	0.9	0.9	0.9	0	1

41.9149	12.4834	0	0.9	0.75	0.6	0	1
41.9149	12.4834	0	0.9	0.5	0.7	0	1
41.9149	12.4834	0	0.9	0.4	0.5	0	1
41.9149	12.4834	0	0.9	0	0	0	1
41.9149	12.4834	0	0.75	0.9	0.9	0	1
41.9149	12.4834	0	0.75	0.75	0.6	0	1
41.9149	12.4834	0	0.75	0.5	0.7	0	1
41.9149	12.4834	0	0.75	0.4	0.5	0	1
41.9149	12.4834	0	0.75	0	0	0	1
41.9149	12.4834	0	0.5	0.9	0.9	0	1
41.9149	12.4834	0	0.5	0.75	0.6	0	1
41.9149	12.4834	0	0.5	0.5	0.7	0	1
41.9149	12.4834	0	0.5	0.4	0.5	0	1
41.9149	12.4834	0	0.5	0	0	0	1
41.9149	12.4834	0	0.45	0.9	0.9	0	1
41.9149	12.4834	0	0.45	0.75	0.6	0	1
41.9149	12.4834	0	0.45	0.5	0.7	0	1
41.9149	12.4834	0	0.45	0.4	0.5	0	1
41.9149	12.4834	0	0.45	0	0	0	1
41.9149	12.4834	0	0	0.9	0.9	1	0
41.9149	12.4834	0	0	0.75	0.6	1	0
41.9149	12.4834	0	0	0.5	0.7	1	0
41.9149	12.4834	0	0	0.4	0.5	1	0
41.9149	12.4834	0	0	0	0	1	0
41.9157	12.4834	0.9	0.9	0.9	0.9	0	1
41.9157	12.4834	0.9	0.9	0.75	0.6	0	1
41.9157	12.4834	0.9	0.9	0.5	0.7	0	1
41.9157	12.4834	0.9	0.9	0.4	0.5	1	0
41.9157	12.4834	0.9	0.9	0	0	1	0
41.9157	12.4834	0.9	0.75	0.9	0.9	0	1
41.9157	12.4834	0.9	0.75	0.75	0.6	0	1
41.9157	12.4834	0.9	0.75	0.5	0.7	0	1
41.9157	12.4834	0.9	0.75	0.4	0.5	1	0
41.9157	12.4834	0.9	0.75	0	0	1	0
41.9157	12.4834	0.9	0.5	0.9	0.9	0	1
41.9157	12.4834	0.9	0.5	0.75	0.6	0	1
41.9157	12.4834	0.9	0.5	0.5	0.7	0	1
41.9157	12.4834	0.9	0.5	0.4	0.5	1	0
41.9157	12.4834	0.9	0.5	0	0	1	0
41.9157	12.4834	0.9	0.45	0.9	0.9	0	1
41.9157	12.4834	0.9	0.45	0.75	0.6	0	1
41.9157	12.4834	0.9	0.45	0.5	0.7	0	1
41.9157	12.4834	0.9	0.45	0.4	0.5	1	0
41.9157	12.4834	0.9	0.45	0	0	1	0
41.9157	12.4834	0.9	0	0.9	0.9	1	0
41.9157	12.4834	0.9	0	0.75	0.6	1	0

41.9157	12.4834	0.9	0	0.5	0.7	1	0
41.9157	12.4834	0.9	0	0.4	0.5	1	0
41.9157	12.4834	0.9	0	0	0	1	0
41.9157	12.4834	0.75	0.9	0.9	0.9	0	1
41.9157	12.4834	0.75	0.9	0.75	0.6	0	1
41.9157	12.4834	0.75	0.9	0.5	0.7	0	1
41.9157	12.4834	0.75	0.9	0.4	0.5	1	0
41.9157	12.4834	0.75	0.9	0	0	1	0
41.9157	12.4834	0.75	0.75	0.9	0.9	0	1
41.9157	12.4834	0.75	0.75	0.75	0.6	0	1
41.9157	12.4834	0.75	0.75	0.5	0.7	0	1
41.9157	12.4834	0.75	0.75	0.4	0.5	1	0
41.9157	12.4834	0.75	0.75	0	0	1	0
41.9157	12.4834	0.75	0.5	0.9	0.9	0	1
41.9157	12.4834	0.75	0.5	0.75	0.6	0	1
41.9157	12.4834	0.75	0.5	0.5	0.7	0	1
41.9157	12.4834	0.75	0.5	0.4	0.5	1	0
41.9157	12.4834	0.75	0.5	0	0	1	0
41.9157	12.4834	0.75	0.45	0.9	0.9	0	1
41.9157	12.4834	0.75	0.45	0.75	0.6	0	1
41.9157	12.4834	0.75	0.45	0.5	0.7	0	1
41.9157	12.4834	0.75	0.45	0.4	0.5	1	0
41.9157	12.4834	0.75	0.45	0	0	1	0
41.9157	12.4834	0.75	0	0.9	0.9	1	0
41.9157	12.4834	0.75	0	0.75	0.6	1	0
41.9157	12.4834	0.75	0	0.5	0.7	1	0
41.9157	12.4834	0.75	0	0.4	0.5	1	0
41.9157	12.4834	0.75	0	0	0	1	0
41.9157	12.4834	0.6	0.9	0.9	0.9	0	1
41.9157	12.4834	0.6	0.9	0.75	0.6	0	1
41.9157	12.4834	0.6	0.9	0.5	0.7	0	1
41.9157	12.4834	0.6	0.9	0.4	0.5	1	1
41.9157	12.4834	0.6	0.9	0	0	1	1
41.9157	12.4834	0.6	0.75	0.9	0.9	0	1
41.9157	12.4834	0.6	0.75	0.75	0.6	0	1
41.9157	12.4834	0.6	0.75	0.5	0.7	0	1
41.9157	12.4834	0.6	0.75	0.4	0.5	1	0
41.9157	12.4834	0.6	0.75	0	0	1	0
41.9157	12.4834	0.6	0.5	0.9	0.9	0	1
41.9157	12.4834	0.6	0.5	0.75	0.6	0	1
41.9157	12.4834	0.6	0.5	0.5	0.7	0	1
41.9157	12.4834	0.6	0.5	0.4	0.5	1	0
41.9157	12.4834	0.6	0.5	0	0	1	0
41.9157	12.4834	0.6	0.45	0.9	0.9	0	1
41.9157	12.4834	0.6	0.45	0.75	0.6	0	1
41.9157	12.4834	0.6	0.45	0.5	0.7	0	1

41.9157	12.4834	0.6	0.45	0.4	0.5	1	0
41.9157	12.4834	0.6	0.45	0	0	1	0
41.9157	12.4834	0.6	0	0.9	0.9	1	0
41.9157	12.4834	0.6	0	0.75	0.6	1	0
41.9157	12.4834	0.6	0	0.5	0.7	1	0
41.9157	12.4834	0.6	0	0.4	0.5	1	0
41.9157	12.4834	0.6	0	0	0	1	0
41.9157	12.4834	0.5	0.9	0.9	0.9	0	1
41.9157	12.4834	0.5	0.9	0.75	0.6	0	1
41.9157	12.4834	0.5	0.9	0.5	0.7	0	1
41.9157	12.4834	0.5	0.9	0.4	0.5	1	0
41.9157	12.4834	0.5	0.9	0	0	1	0
41.9157	12.4834	0.5	0.75	0.9	0.9	0	1
41.9157	12.4834	0.5	0.75	0.75	0.6	0	1
41.9157	12.4834	0.5	0.75	0.5	0.7	0	1
41.9157	12.4834	0.5	0.75	0.4	0.5	1	0
41.9157	12.4834	0.5	0.75	0	0	1	0
41.9157	12.4834	0.5	0.5	0.9	0.9	0	1
41.9157	12.4834	0.5	0.5	0.75	0.6	0	1
41.9157	12.4834	0.5	0.5	0.5	0.7	0	1
41.9157	12.4834	0.5	0.5	0.4	0.5	1	0
41.9157	12.4834	0.5	0.5	0	0	1	0
41.9157	12.4834	0.5	0.45	0.9	0.9	0	1
41.9157	12.4834	0.5	0.45	0.75	0.6	0	1
41.9157	12.4834	0.5	0.45	0.5	0.7	0	1
41.9157	12.4834	0.5	0.45	0.4	0.5	1	0
41.9157	12.4834	0.5	0.45	0	0	1	0
41.9157	12.4834	0.5	0	0.9	0.9	1	0
41.9157	12.4834	0.5	0	0.75	0.6	1	0
41.9157	12.4834	0.5	0	0.5	0.7	1	0
41.9157	12.4834	0.5	0	0.4	0.5	1	0
41.9157	12.4834	0.5	0	0	0	1	0
41.9157	12.4834	0.35	0.9	0.9	0.9	0	1
41.9157	12.4834	0.35	0.9	0.75	0.6	0	1
41.9157	12.4834	0.35	0.9	0.5	0.7	0	1
41.9157	12.4834	0.35	0.9	0.4	0.5	1	0
41.9157	12.4834	0.35	0.9	0	0	1	0
41.9157	12.4834	0.35	0.75	0.9	0.9	0	1
41.9157	12.4834	0.35	0.75	0.75	0.6	0	1
41.9157	12.4834	0.35	0.75	0.5	0.7	0	1
41.9157	12.4834	0.35	0.75	0.4	0.5	1	0
41.9157	12.4834	0.35	0.75	0	0	1	0
41.9157	12.4834	0.35	0.5	0.9	0.9	0	1
41.9157	12.4834	0.35	0.5	0.75	0.6	0	1
41.9157	12.4834	0.35	0.5	0.5	0.7	0	1
41.9157	12.4834	0.35	0.5	0.4	0.5	1	0

41.9157	12.4834	0.35	0.5	0	0	1	0
41.9157	12.4834	0.35	0.45	0.9	0.9	0	1
41.9157	12.4834	0.35	0.45	0.75	0.6	0	1
41.9157	12.4834	0.35	0.45	0.5	0.7	0	1
41.9157	12.4834	0.35	0.45	0.4	0.5	1	0
41.9157	12.4834	0.35	0.45	0	0	1	0
41.9157	12.4834	0.35	0	0.9	0.9	1	0
41.9157	12.4834	0.35	0	0.75	0.6	1	0
41.9157	12.4834	0.35	0	0.5	0.7	1	0
41.9157	12.4834	0.35	0	0.4	0.5	1	0
41.9157	12.4834	0.35	0	0	0	1	0
41.9157	12.4834	0.2	0.9	0.9	0.9	0	1
41.9157	12.4834	0.2	0.9	0.75	0.6	0	1
41.9157	12.4834	0.2	0.9	0.5	0.7	0	1
41.9157	12.4834	0.2	0.9	0.4	0.5	1	0
41.9157	12.4834	0.2	0.9	0	0	1	0
41.9157	12.4834	0.2	0.75	0.9	0.9	0	1
41.9157	12.4834	0.2	0.75	0.75	0.6	0	1
41.9157	12.4834	0.2	0.75	0.5	0.7	0	1
41.9157	12.4834	0.2	0.75	0.4	0.5	1	0
41.9157	12.4834	0.2	0.75	0	0	1	0
41.9157	12.4834	0.2	0.5	0.9	0.9	0	1
41.9157	12.4834	0.2	0.5	0.75	0.6	0	1
41.9157	12.4834	0.2	0.5	0.5	0.7	0	1
41.9157	12.4834	0.2	0.5	0.4	0.5	1	0
41.9157	12.4834	0.2	0.5	0	0	1	0
41.9157	12.4834	0.2	0.45	0.9	0.9	0	1
41.9157	12.4834	0.2	0.45	0.75	0.6	0	1
41.9157	12.4834	0.2	0.45	0.5	0.7	0	1
41.9157	12.4834	0.2	0.45	0.4	0.5	1	0
41.9157	12.4834	0.2	0.45	0	0	1	0
41.9157	12.4834	0.2	0	0.9	0.9	1	0
41.9157	12.4834	0.2	0	0.75	0.6	1	0
41.9157	12.4834	0.2	0	0.5	0.7	1	0
41.9157	12.4834	0.2	0	0.4	0.5	1	0
41.9157	12.4834	0.2	0	0	0	1	0
41.9157	12.4834	0	0.9	0.9	0.9	0	1
41.9157	12.4834	0	0.9	0.75	0.6	0	1
41.9157	12.4834	0	0.9	0.5	0.7	0	1
41.9157	12.4834	0	0.9	0.4	0.5	0	1
41.9157	12.4834	0	0.9	0	0	0	1
41.9157	12.4834	0	0.75	0.9	0.9	0	1
41.9157	12.4834	0	0.75	0.75	0.6	0	1
41.9157	12.4834	0	0.75	0.5	0.7	0	1
41.9157	12.4834	0	0.75	0.4	0.5	0	1
41.9157	12.4834	0	0.75	0	0	0	1

41.9157	12.4834	0	0.5	0.9	0.9	0	1
41.9157	12.4834	0	0.5	0.75	0.6	0	1
41.9157	12.4834	0	0.5	0.5	0.7	0	1
41.9157	12.4834	0	0.5	0.4	0.5	0	1
41.9157	12.4834	0	0.5	0	0	0	1
41.9157	12.4834	0	0.45	0.9	0.9	0	1
41.9157	12.4834	0	0.45	0.75	0.6	0	1
41.9157	12.4834	0	0.45	0.5	0.7	0	1
41.9157	12.4834	0	0.45	0.4	0.5	0	1
41.9157	12.4834	0	0.45	0	0	0	1
41.9157	12.4834	0	0	0.9	0.9	1	0
41.9157	12.4834	0	0	0.75	0.6	1	0
41.9157	12.4834	0	0	0.5	0.7	1	0
41.9157	12.4834	0	0	0.4	0.5	1	0
41.9157	12.4834	0	0	0	0	1	0
41.9198	12.4801	0.9	0.9	0.9	0.9	0	1
41.9198	12.4801	0.9	0.75	0.75	0.75	0	1
41.9198	12.4801	0.9	0.5	0.5	0.5	0	1
41.9198	12.4801	0.9	0.45	0.45	0.45	0	1
41.9198	12.4801	0.9	0	0	0	1	0
41.9198	12.4801	0.75	0.9	0.9	0.9	0	1
41.9198	12.4801	0.75	0.75	0.75	0.75	0	1
41.9198	12.4801	0.75	0.5	0.5	0.5	0	1
41.9198	12.4801	0.75	0.45	0.45	0.45	0	1
41.9198	12.4801	0.75	0	0	0	1	0
41.9198	12.4801	0.6	0.9	0.9	0.9	0	1
41.9198	12.4801	0.6	0.75	0.75	0.75	0	1
41.9198	12.4801	0.6	0.5	0.5	0.5	0	1
41.9198	12.4801	0.6	0.3	0.3	0.3	0	1
41.9198	12.4801	0.6	0	0	0	1	0
41.9198	12.4801	0.5	0.9	0.9	0.9	0	1
41.9198	12.4801	0.5	0.75	0.75	0.75	0	1
41.9198	12.4801	0.5	0.5	0.5	0.5	0	1
41.9198	12.4801	0.5	0.3	0.3	0.3	0	1
41.9198	12.4801	0.5	0	0	0	1	0
41.9198	12.4801	0.35	0.9	0.9	0.9	0	1
41.9198	12.4801	0.35	0.75	0.75	0.75	0	1
41.9198	12.4801	0.35	0.5	0.5	0.5	0	1
41.9198	12.4801	0.35	0.3	0.3	0.3	0	1
41.9198	12.4801	0.35	0	0	0	1	0
41.9198	12.4801	0.2	0.9	0.9	0.9	0	1
41.9198	12.4801	0.2	0.75	0.75	0.75	0	1
41.9198	12.4801	0.2	0.5	0.5	0.5	0	1
41.9198	12.4801	0.2	0.3	0.3	0.3	0	1
41.9198	12.4801	0.2	0	0	0	1	0
41.9198	12.4801	0	0.9	0.9	0.9	0	1

41.9198	12.4801	0	0.75	0.75	0.75	0	1
41.9198	12.4801	0	0.5	0.5	0.5	0	1
41.9198	12.4801	0	0.3	0.3	0.3	0	1
41.9198	12.4801	0	0	0	0	0	1
41.965	12.4605	0.9	0.9	0.9	0.9	1	0
41.965	12.4605	0.9	0.9	0.75	0.6	1	0
41.965	12.4605	0.9	0.9	0.5	0.7	1	0
41.965	12.4605	0.9	0.9	0.4	0.5	0	1
41.965	12.4605	0.9	0.9	0	0	0	1
41.965	12.4605	0.9	0.75	0.9	0.9	1	0
41.965	12.4605	0.9	0.75	0.75	0.6	1	0
41.965	12.4605	0.9	0.75	0.5	0.7	1	0
41.965	12.4605	0.9	0.75	0.4	0.5	0	1
41.965	12.4605	0.9	0.75	0	0	0	1
41.965	12.4605	0.9	0.5	0.9	0.9	1	0
41.965	12.4605	0.9	0.5	0.75	0.6	1	0
41.965	12.4605	0.9	0.5	0.5	0.7	1	0
41.965	12.4605	0.9	0.5	0.4	0.5	0	1
41.965	12.4605	0.9	0.5	0	0	0	1
41.965	12.4605	0.9	0.45	0.9	0.9	1	0
41.965	12.4605	0.9	0.45	0.75	0.6	1	0
41.965	12.4605	0.9	0.45	0.5	0.7	1	0
41.965	12.4605	0.9	0.45	0.4	0.5	0	1
41.965	12.4605	0.9	0.45	0	0	0	1
41.965	12.4605	0.9	0	0.9	0.9	1	0
41.965	12.4605	0.9	0	0.75	0.6	1	0
41.965	12.4605	0.9	0	0.5	0.7	1	0
41.965	12.4605	0.9	0	0.4	0.5	1	0
41.965	12.4605	0.9	0	0	0	1	0
41.965	12.4605	0.75	0.9	0.9	0.9	1	0
41.965	12.4605	0.75	0.9	0.75	0.6	1	0
41.965	12.4605	0.75	0.9	0.5	0.7	1	0
41.965	12.4605	0.75	0.9	0.4	0.5	0	1
41.965	12.4605	0.75	0.9	0	0	0	1
41.965	12.4605	0.75	0.75	0.9	0.9	1	0
41.965	12.4605	0.75	0.75	0.75	0.6	1	0
41.965	12.4605	0.75	0.75	0.5	0.7	1	0
41.965	12.4605	0.75	0.75	0.4	0.5	0	1
41.965	12.4605	0.75	0.75	0	0	0	1
41.965	12.4605	0.75	0.5	0.9	0.9	1	0
41.965	12.4605	0.75	0.5	0.75	0.6	1	0
41.965	12.4605	0.75	0.5	0.5	0.7	1	0
41.965	12.4605	0.75	0.5	0.4	0.5	0	1
41.965	12.4605	0.75	0.5	0	0	0	1
41.965	12.4605	0.75	0.45	0.9	0.9	1	0
41.965	12.4605	0.75	0.45	0.75	0.6	1	0

41.965	12.4605	0.75	0.45	0.5	0.7	1	0
41.965	12.4605	0.75	0.45	0.4	0.5	0	1
41.965	12.4605	0.75	0.45	0	0	0	1
41.965	12.4605	0.75	0	0.9	0.9	1	0
41.965	12.4605	0.75	0	0.75	0.6	1	0
41.965	12.4605	0.75	0	0.5	0.7	1	0
41.965	12.4605	0.75	0	0.4	0.5	1	0
41.965	12.4605	0.75	0	0	0	1	0
41.965	12.4605	0.6	0.9	0.9	0.9	1	0
41.965	12.4605	0.6	0.9	0.75	0.6	1	0
41.965	12.4605	0.6	0.9	0.5	0.7	1	0
41.965	12.4605	0.6	0.9	0.4	0.5	0	1
41.965	12.4605	0.6	0.9	0	0	0	1
41.965	12.4605	0.6	0.75	0.9	0.9	1	0
41.965	12.4605	0.6	0.75	0.75	0.6	1	0
41.965	12.4605	0.6	0.75	0.5	0.7	1	0
41.965	12.4605	0.6	0.75	0.4	0.5	0	1
41.965	12.4605	0.6	0.75	0	0	0	1
41.965	12.4605	0.6	0.5	0.9	0.9	1	0
41.965	12.4605	0.6	0.5	0.75	0.6	1	0
41.965	12.4605	0.6	0.5	0.5	0.7	1	0
41.965	12.4605	0.6	0.5	0.4	0.5	0	1
41.965	12.4605	0.6	0.5	0	0	0	1
41.965	12.4605	0.6	0.45	0.9	0.9	1	0
41.965	12.4605	0.6	0.45	0.75	0.6	1	0
41.965	12.4605	0.6	0.45	0.5	0.7	1	0
41.965	12.4605	0.6	0.45	0.4	0.5	0	1
41.965	12.4605	0.6	0.45	0	0	0	1
41.965	12.4605	0.6	0	0.9	0.9	1	0
41.965	12.4605	0.6	0	0.75	0.6	1	0
41.965	12.4605	0.6	0	0.5	0.7	1	0
41.965	12.4605	0.6	0	0.4	0.5	1	0
41.965	12.4605	0.6	0	0	0	1	0
41.965	12.4605	0.5	0.9	0.9	0.9	1	0
41.965	12.4605	0.5	0.9	0.75	0.6	1	0
41.965	12.4605	0.5	0.9	0.5	0.7	1	0
41.965	12.4605	0.5	0.9	0.4	0.5	0	1
41.965	12.4605	0.5	0.9	0	0	0	1
41.965	12.4605	0.5	0.75	0.9	0.9	1	0
41.965	12.4605	0.5	0.75	0.75	0.6	1	0
41.965	12.4605	0.5	0.75	0.5	0.7	1	0
41.965	12.4605	0.5	0.75	0.4	0.5	0	1
41.965	12.4605	0.5	0.75	0	0	0	1
41.965	12.4605	0.5	0.5	0.9	0.9	1	0
41.965	12.4605	0.5	0.5	0.75	0.6	1	0
41.965	12.4605	0.5	0.5	0.5	0.7	1	0

41.965	12.4605	0.5	0.5	0.4	0.5	0	1
41.965	12.4605	0.5	0.5	0	0	0	1
41.965	12.4605	0.5	0.45	0.9	0.9	1	0
41.965	12.4605	0.5	0.45	0.75	0.6	1	0
41.965	12.4605	0.5	0.45	0.5	0.7	1	0
41.965	12.4605	0.5	0.45	0.4	0.5	0	1
41.965	12.4605	0.5	0.45	0	0	0	1
41.965	12.4605	0.5	0	0.9	0.9	1	0
41.965	12.4605	0.5	0	0.75	0.6	1	0
41.965	12.4605	0.5	0	0.5	0.7	1	0
41.965	12.4605	0.5	0	0.4	0.5	1	0
41.965	12.4605	0.5	0	0	0	1	0
41.965	12.4605	0.35	0.9	0.9	0.9	1	0
41.965	12.4605	0.35	0.9	0.75	0.6	1	0
41.965	12.4605	0.35	0.9	0.5	0.7	1	0
41.965	12.4605	0.35	0.9	0.4	0.5	0	1
41.965	12.4605	0.35	0.9	0	0	0	1
41.965	12.4605	0.35	0.75	0.9	0.9	1	0
41.965	12.4605	0.35	0.75	0.75	0.6	1	0
41.965	12.4605	0.35	0.75	0.5	0.7	1	0
41.965	12.4605	0.35	0.75	0.4	0.5	0	1
41.965	12.4605	0.35	0.75	0	0	0	1
41.965	12.4605	0.35	0.5	0.9	0.9	1	0
41.965	12.4605	0.35	0.5	0.75	0.6	1	0
41.965	12.4605	0.35	0.5	0.5	0.7	1	0
41.965	12.4605	0.35	0.5	0.4	0.5	0	1
41.965	12.4605	0.35	0.5	0	0	0	1
41.965	12.4605	0.35	0.45	0.9	0.9	1	0
41.965	12.4605	0.35	0.45	0.75	0.6	1	0
41.965	12.4605	0.35	0.45	0.5	0.7	1	0
41.965	12.4605	0.35	0.45	0.4	0.5	0	1
41.965	12.4605	0.35	0.45	0	0	0	1
41.965	12.4605	0.35	0	0.9	0.9	1	0
41.965	12.4605	0.35	0	0.75	0.6	1	0
41.965	12.4605	0.35	0	0.5	0.7	1	0
41.965	12.4605	0.35	0	0.4	0.5	1	0
41.965	12.4605	0.35	0	0	0	1	0
41.965	12.4605	0.2	0.9	0.9	0.9	1	0
41.965	12.4605	0.2	0.9	0.75	0.6	1	0
41.965	12.4605	0.2	0.9	0.5	0.7	1	0
41.965	12.4605	0.2	0.9	0.4	0.5	0	1
41.965	12.4605	0.2	0.9	0	0	0	1
41.965	12.4605	0.2	0.75	0.9	0.9	1	0
41.965	12.4605	0.2	0.75	0.75	0.6	1	0
41.965	12.4605	0.2	0.75	0.5	0.7	1	0
41.965	12.4605	0.2	0.75	0.4	0.5	0	1

41.965	12.4605	0.2	0.75	0	0	0	1
41.965	12.4605	0.2	0.5	0.9	0.9	1	0
41.965	12.4605	0.2	0.5	0.75	0.6	1	0
41.965	12.4605	0.2	0.5	0.5	0.7	1	0
41.965	12.4605	0.2	0.5	0.4	0.5	0	1
41.965	12.4605	0.2	0.5	0	0	0	1
41.965	12.4605	0.2	0.45	0.9	0.9	1	0
41.965	12.4605	0.2	0.45	0.75	0.6	1	0
41.965	12.4605	0.2	0.45	0.5	0.7	1	0
41.965	12.4605	0.2	0.45	0.4	0.5	0	1
41.965	12.4605	0.2	0.45	0	0	0	1
41.965	12.4605	0.2	0	0.9	0.9	1	0
41.965	12.4605	0.2	0	0.75	0.6	1	0
41.965	12.4605	0.2	0	0.5	0.7	1	0
41.965	12.4605	0.2	0	0.4	0.5	1	0
41.965	12.4605	0.2	0	0	0	1	0
41.965	12.4605	0	0.9	0.9	0.9	0	1
41.965	12.4605	0	0.9	0.75	0.6	0	1
41.965	12.4605	0	0.9	0.5	0.7	0	1
41.965	12.4605	0	0.9	0.4	0.5	0	1
41.965	12.4605	0	0.9	0	0	0	1
41.965	12.4605	0	0.75	0.9	0.9	0	1
41.965	12.4605	0	0.75	0.75	0.6	0	1
41.965	12.4605	0	0.75	0.5	0.7	0	1
41.965	12.4605	0	0.75	0.4	0.5	0	1
41.965	12.4605	0	0.75	0	0	0	1
41.965	12.4605	0	0.5	0.9	0.9	0	1
41.965	12.4605	0	0.5	0.75	0.6	0	1
41.965	12.4605	0	0.5	0.5	0.7	0	1
41.965	12.4605	0	0.5	0.4	0.5	0	1
41.965	12.4605	0	0.5	0	0	0	1
41.965	12.4605	0	0.45	0.9	0.9	0	1
41.965	12.4605	0	0.45	0.75	0.6	0	1
41.965	12.4605	0	0.45	0.5	0.7	0	1
41.965	12.4605	0	0.45	0.4	0.5	0	1
41.965	12.4605	0	0.45	0	0	0	1
41.965	12.4605	0	0	0.9	0.9	0	1
41.965	12.4605	0	0	0.75	0.6	0	1
41.965	12.4605	0	0	0.5	0.7	0	1
41.965	12.4605	0	0	0.4	0.5	0	1
41.965	12.4605	0	0	0	0	0	1
41.9795	12.4403	0.9	0.9	0.9	0.9	1	0
41.9795	12.4403	0.9	0.9	0.75	0.6	1	0
41.9795	12.4403	0.9	0.9	0.5	0.7	1	0
41.9795	12.4403	0.9	0.9	0.4	0.5	0	1
41.9795	12.4403	0.9	0.9	0	0	0	1

41.9795	12.4403	0.9	0.75	0.9	0.9	1	0
41.9795	12.4403	0.9	0.75	0.75	0.6	1	0
41.9795	12.4403	0.9	0.75	0.5	0.7	1	0
41.9795	12.4403	0.9	0.75	0.4	0.5	0	1
41.9795	12.4403	0.9	0.75	0	0	0	1
41.9795	12.4403	0.9	0.5	0.9	0.9	1	0
41.9795	12.4403	0.9	0.5	0.75	0.6	1	0
41.9795	12.4403	0.9	0.5	0.5	0.7	1	0
41.9795	12.4403	0.9	0.5	0.4	0.5	0	1
41.9795	12.4403	0.9	0.5	0	0	0	1
41.9795	12.4403	0.9	0.45	0.9	0.9	1	0
41.9795	12.4403	0.9	0.45	0.75	0.6	1	0
41.9795	12.4403	0.9	0.45	0.5	0.7	1	0
41.9795	12.4403	0.9	0.45	0.4	0.5	0	1
41.9795	12.4403	0.9	0.45	0	0	0	1
41.9795	12.4403	0.9	0	0.9	0.9	1	0
41.9795	12.4403	0.9	0	0.75	0.6	1	0
41.9795	12.4403	0.9	0	0.5	0.7	1	0
41.9795	12.4403	0.9	0	0.4	0.5	1	0
41.9795	12.4403	0.9	0	0	0	1	0
41.9795	12.4403	0.75	0.9	0.9	0.9	1	0
41.9795	12.4403	0.75	0.9	0.75	0.6	1	0
41.9795	12.4403	0.75	0.9	0.5	0.7	1	0
41.9795	12.4403	0.75	0.9	0.4	0.5	0	1
41.9795	12.4403	0.75	0.9	0	0	0	1
41.9795	12.4403	0.75	0.75	0.9	0.9	1	0
41.9795	12.4403	0.75	0.75	0.75	0.6	1	0
41.9795	12.4403	0.75	0.75	0.5	0.7	1	0
41.9795	12.4403	0.75	0.75	0.4	0.5	0	1
41.9795	12.4403	0.75	0.75	0	0	0	1
41.9795	12.4403	0.75	0.5	0.9	0.9	1	0
41.9795	12.4403	0.75	0.5	0.75	0.6	1	0
41.9795	12.4403	0.75	0.5	0.5	0.7	1	0
41.9795	12.4403	0.75	0.5	0.4	0.5	0	1
41.9795	12.4403	0.75	0.5	0	0	0	1
41.9795	12.4403	0.75	0.45	0.9	0.9	1	0
41.9795	12.4403	0.75	0.45	0.75	0.6	1	0
41.9795	12.4403	0.75	0.45	0.5	0.7	1	0
41.9795	12.4403	0.75	0.45	0.4	0.5	0	1
41.9795	12.4403	0.75	0.45	0	0	0	1
41.9795	12.4403	0.75	0	0.9	0.9	1	0
41.9795	12.4403	0.75	0	0.75	0.6	1	0
41.9795	12.4403	0.75	0	0.5	0.7	1	0
41.9795	12.4403	0.75	0	0.4	0.5	1	0
41.9795	12.4403	0.75	0	0	0	1	0
41.9795	12.4403	0.6	0.9	0.9	0.9	1	0

41.9795	12.4403	0.6	0.9	0.75	0.6	1	0
41.9795	12.4403	0.6	0.9	0.5	0.7	1	0
41.9795	12.4403	0.6	0.9	0.4	0.5	0	1
41.9795	12.4403	0.6	0.9	0	0	0	1
41.9795	12.4403	0.6	0.75	0.9	0.9	1	0
41.9795	12.4403	0.6	0.75	0.75	0.6	1	0
41.9795	12.4403	0.6	0.75	0.5	0.7	1	0
41.9795	12.4403	0.6	0.75	0.4	0.5	0	1
41.9795	12.4403	0.6	0.75	0	0	0	1
41.9795	12.4403	0.6	0.5	0.9	0.9	1	0
41.9795	12.4403	0.6	0.5	0.75	0.6	1	0
41.9795	12.4403	0.6	0.5	0.5	0.7	1	0
41.9795	12.4403	0.6	0.5	0.4	0.5	0	1
41.9795	12.4403	0.6	0.5	0	0	0	1
41.9795	12.4403	0.6	0.45	0.9	0.9	1	0
41.9795	12.4403	0.6	0.45	0.75	0.6	1	0
41.9795	12.4403	0.6	0.45	0.5	0.7	1	0
41.9795	12.4403	0.6	0.45	0.4	0.5	0	1
41.9795	12.4403	0.6	0.45	0	0	0	1
41.9795	12.4403	0.6	0	0.9	0.9	1	0
41.9795	12.4403	0.6	0	0.75	0.6	1	0
41.9795	12.4403	0.6	0	0.5	0.7	1	0
41.9795	12.4403	0.6	0	0.4	0.5	1	0
41.9795	12.4403	0.6	0	0	0	1	0
41.9795	12.4403	0.5	0.9	0.9	0.9	1	0
41.9795	12.4403	0.5	0.9	0.75	0.6	1	0
41.9795	12.4403	0.5	0.9	0.5	0.7	1	0
41.9795	12.4403	0.5	0.9	0.4	0.5	0	1
41.9795	12.4403	0.5	0.9	0	0	0	1
41.9795	12.4403	0.5	0.75	0.9	0.9	1	0
41.9795	12.4403	0.5	0.75	0.75	0.6	1	0
41.9795	12.4403	0.5	0.75	0.5	0.7	1	0
41.9795	12.4403	0.5	0.75	0.4	0.5	0	1
41.9795	12.4403	0.5	0.75	0	0	0	1
41.9795	12.4403	0.5	0.5	0.9	0.9	1	0
41.9795	12.4403	0.5	0.5	0.75	0.6	1	0
41.9795	12.4403	0.5	0.5	0.5	0.7	1	0
41.9795	12.4403	0.5	0.5	0.4	0.5	0	1
41.9795	12.4403	0.5	0.5	0	0	0	1
41.9795	12.4403	0.5	0.45	0.9	0.9	1	0
41.9795	12.4403	0.5	0.45	0.75	0.6	1	0
41.9795	12.4403	0.5	0.45	0.5	0.7	1	0
41.9795	12.4403	0.5	0.45	0.4	0.5	0	1
41.9795	12.4403	0.5	0.45	0	0	0	1
41.9795	12.4403	0.5	0	0.9	0.9	1	0
41.9795	12.4403	0.5	0	0.75	0.6	1	0

41.9795	12.4403	0.5	0	0.5	0.7	1	0
41.9795	12.4403	0.5	0	0.4	0.5	1	0
41.9795	12.4403	0.5	0	0	0	1	0
41.9795	12.4403	0.35	0.9	0.9	0.9	1	0
41.9795	12.4403	0.35	0.9	0.75	0.6	1	0
41.9795	12.4403	0.35	0.9	0.5	0.7	1	0
41.9795	12.4403	0.35	0.9	0.4	0.5	0	1
41.9795	12.4403	0.35	0.9	0	0	0	1
41.9795	12.4403	0.35	0.75	0.9	0.9	1	0
41.9795	12.4403	0.35	0.75	0.75	0.6	1	0
41.9795	12.4403	0.35	0.75	0.5	0.7	1	0
41.9795	12.4403	0.35	0.75	0.4	0.5	0	1
41.9795	12.4403	0.35	0.75	0	0	0	1
41.9795	12.4403	0.35	0.5	0.9	0.9	1	0
41.9795	12.4403	0.35	0.5	0.75	0.6	1	0
41.9795	12.4403	0.35	0.5	0.5	0.7	1	0
41.9795	12.4403	0.35	0.5	0.4	0.5	0	1
41.9795	12.4403	0.35	0.5	0	0	0	1
41.9795	12.4403	0.35	0.45	0.9	0.9	1	0
41.9795	12.4403	0.35	0.45	0.75	0.6	1	0
41.9795	12.4403	0.35	0.45	0.5	0.7	1	0
41.9795	12.4403	0.35	0.45	0.4	0.5	0	1
41.9795	12.4403	0.35	0.45	0	0	0	1
41.9795	12.4403	0.35	0	0.9	0.9	1	0
41.9795	12.4403	0.35	0	0.75	0.6	1	0
41.9795	12.4403	0.35	0	0.5	0.7	1	0
41.9795	12.4403	0.35	0	0.4	0.5	1	0
41.9795	12.4403	0.35	0	0	0	1	0
41.9795	12.4403	0.2	0.9	0.9	0.9	1	0
41.9795	12.4403	0.2	0.9	0.75	0.6	1	0
41.9795	12.4403	0.2	0.9	0.5	0.7	1	0
41.9795	12.4403	0.2	0.9	0.4	0.5	0	1
41.9795	12.4403	0.2	0.9	0	0	0	1
41.9795	12.4403	0.2	0.75	0.9	0.9	1	0
41.9795	12.4403	0.2	0.75	0.75	0.6	1	0
41.9795	12.4403	0.2	0.75	0.5	0.7	1	0
41.9795	12.4403	0.2	0.75	0.4	0.5	0	1
41.9795	12.4403	0.2	0.75	0	0	0	1
41.9795	12.4403	0.2	0.5	0.9	0.9	1	0
41.9795	12.4403	0.2	0.5	0.75	0.6	1	0
41.9795	12.4403	0.2	0.5	0.5	0.7	1	0
41.9795	12.4403	0.2	0.5	0.4	0.5	0	1
41.9795	12.4403	0.2	0.5	0	0	0	1
41.9795	12.4403	0.2	0.45	0.9	0.9	1	0
41.9795	12.4403	0.2	0.45	0.75	0.6	1	0
41.9795	12.4403	0.2	0.45	0.5	0.7	1	0

41.9795	12.4403	0.2	0.45	0.4	0.5	0	1
41.9795	12.4403	0.2	0.45	0	0	0	1
41.9795	12.4403	0.2	0	0.9	0.9	1	0
41.9795	12.4403	0.2	0	0.75	0.6	1	0
41.9795	12.4403	0.2	0	0.5	0.7	1	0
41.9795	12.4403	0.2	0	0.4	0.5	1	0
41.9795	12.4403	0.2	0	0	0	1	0
41.9795	12.4403	0	0.9	0.9	0.9	0	1
41.9795	12.4403	0	0.9	0.75	0.6	0	1
41.9795	12.4403	0	0.9	0.5	0.7	0	1
41.9795	12.4403	0	0.9	0.4	0.5	0	1
41.9795	12.4403	0	0.9	0	0	0	1
41.9795	12.4403	0	0.75	0.9	0.9	0	1
41.9795	12.4403	0	0.75	0.75	0.6	0	1
41.9795	12.4403	0	0.75	0.5	0.7	0	1
41.9795	12.4403	0	0.75	0.4	0.5	0	1
41.9795	12.4403	0	0.75	0	0	0	1
41.9795	12.4403	0	0.5	0.9	0.9	0	1
41.9795	12.4403	0	0.5	0.75	0.6	0	1
41.9795	12.4403	0	0.5	0.5	0.7	0	1
41.9795	12.4403	0	0.5	0.4	0.5	0	1
41.9795	12.4403	0	0.5	0	0	0	1
41.9795	12.4403	0	0.45	0.9	0.9	0	1
41.9795	12.4403	0	0.45	0.75	0.6	0	1
41.9795	12.4403	0	0.45	0.5	0.7	0	1
41.9795	12.4403	0	0.45	0.4	0.5	0	1
41.9795	12.4403	0	0.45	0	0	0	1
41.9795	12.4403	0	0	0.9	0.9	0	1
41.9795	12.4403	0	0	0.75	0.6	0	1
41.9795	12.4403	0	0	0.5	0.7	0	1
41.9795	12.4403	0	0	0.4	0.5	0	1
41.9795	12.4403	0	0	0	0	0	1
41.9994	12.4271	0.9	0.9	0.9	0.9	1	0
41.9994	12.4271	0.9	0.75	0.75	0.75	1	0
41.9994	12.4271	0.9	0.5	0.5	0.5	1	0
41.9994	12.4271	0.9	0.45	0.45	0.45	1	0
41.9994	12.4271	0.9	0	0	0	1	0
41.9994	12.4271	0.75	0.9	0.9	0.9	1	0
41.9994	12.4271	0.75	0.75	0.75	0.75	1	0
41.9994	12.4271	0.75	0.5	0.5	0.5	1	0
41.9994	12.4271	0.75	0.45	0.45	0.45	1	0
41.9994	12.4271	0.75	0	0	0	1	0
41.9994	12.4271	0.6	0.9	0.9	0.9	1	0
41.9994	12.4271	0.6	0.75	0.75	0.75	1	0
41.9994	12.4271	0.6	0.5	0.5	0.5	1	0
41.9994	12.4271	0.6	0.3	0.3	0.3	1	0

41.9994	12.4271	0.6	0	0	0	1	0
41.9994	12.4271	0.5	0.9	0.9	0.9	1	0
41.9994	12.4271	0.5	0.75	0.75	0.75	1	0
41.9994	12.4271	0.5	0.5	0.5	0.5	1	0
41.9994	12.4271	0.5	0.3	0.3	0.3	1	0
41.9994	12.4271	0.5	0	0	0	1	0
41.9994	12.4271	0.35	0.9	0.9	0.9	1	0
41.9994	12.4271	0.35	0.75	0.75	0.75	1	0
41.9994	12.4271	0.35	0.5	0.5	0.5	1	0
41.9994	12.4271	0.35	0.3	0.3	0.3	1	0
41.9994	12.4271	0.35	0	0	0	1	0
41.9994	12.4271	0.2	0.9	0.9	0.9	1	0
41.9994	12.4271	0.2	0.75	0.75	0.75	1	0
41.9994	12.4271	0.2	0.5	0.5	0.5	1	0
41.9994	12.4271	0.2	0.3	0.3	0.3	1	0
41.9994	12.4271	0.2	0	0	0	1	0
41.9994	12.4271	0	0.9	0.9	0.9	1	0
41.9994	12.4271	0	0.75	0.75	0.75	1	0
41.9994	12.4271	0	0.5	0.5	0.5	1	0
41.9994	12.4271	0	0.3	0.3	0.3	1	0
41.9994	12.4271	0	0	0	0	1	0
42.0442	12.3972	0.9	0.9	0.9	0.9	1	0
42.0442	12.3972	0.9	0.75	0.75	0.75	1	0
42.0442	12.3972	0.9	0.5	0.5	0.5	1	0
42.0442	12.3972	0.9	0.45	0.45	0.45	1	0
42.0442	12.3972	0.9	0	0	0	1	0
42.0442	12.3972	0.75	0.9	0.9	0.9	1	0
42.0442	12.3972	0.75	0.75	0.75	0.75	1	0
42.0442	12.3972	0.75	0.5	0.5	0.5	1	0
42.0442	12.3972	0.75	0.45	0.45	0.45	1	0
42.0442	12.3972	0.75	0	0	0	1	0
42.0442	12.3972	0.6	0.9	0.9	0.9	1	0
42.0442	12.3972	0.6	0.75	0.75	0.75	1	0
42.0442	12.3972	0.6	0.5	0.5	0.5	1	0
42.0442	12.3972	0.6	0.3	0.3	0.3	1	0
42.0442	12.3972	0.6	0	0	0	1	0
42.0442	12.3972	0.5	0.9	0.9	0.9	1	0
42.0442	12.3972	0.5	0.75	0.75	0.75	1	0
42.0442	12.3972	0.5	0.5	0.5	0.5	1	0
42.0442	12.3972	0.5	0.3	0.3	0.3	1	0
42.0442	12.3972	0.5	0	0	0	1	0
42.0442	12.3972	0.35	0.9	0.9	0.9	1	0
42.0442	12.3972	0.35	0.75	0.75	0.75	1	0
42.0442	12.3972	0.35	0.5	0.5	0.5	1	0
42.0442	12.3972	0.35	0.3	0.3	0.3	1	0
42.0442	12.3972	0.35	0	0	0	1	0

42.0442	12.3972	0.2	0.9	0.9	0.9	1	0
42.0442	12.3972	0.2	0.75	0.75	0.75	1	0
42.0442	12.3972	0.2	0.5	0.5	0.5	1	0
42.0442	12.3972	0.2	0.3	0.3	0.3	1	0
42.0442	12.3972	0.2	0	0	0	1	0
42.0442	12.3972	0	0.9	0.9	0.9	1	0
42.0442	12.3972	0	0.75	0.75	0.75	1	0
42.0442	12.3972	0	0.5	0.5	0.5	1	0
42.0442	12.3972	0	0.3	0.3	0.3	1	0
42.0442	12.3972	0	0	0	0	1	0
42.0541	12.3906	0.9	0.9	0.9	0.9	0	1
42.0541	12.3906	0.9	0.9	0.75	0.6	0	1
42.0541	12.3906	0.9	0.9	0.5	0.7	0	1
42.0541	12.3906	0.9	0.9	0.4	0.5	1	0
42.0541	12.3906	0.9	0.9	0	0	1	0
42.0541	12.3906	0.9	0.75	0.9	0.9	0	1
42.0541	12.3906	0.9	0.75	0.75	0.6	0	1
42.0541	12.3906	0.9	0.75	0.5	0.7	0	1
42.0541	12.3906	0.9	0.75	0.4	0.5	1	0
42.0541	12.3906	0.9	0.75	0	0	1	0
42.0541	12.3906	0.9	0.5	0.9	0.9	0	1
42.0541	12.3906	0.9	0.5	0.75	0.6	0	1
42.0541	12.3906	0.9	0.5	0.5	0.7	0	1
42.0541	12.3906	0.9	0.5	0.4	0.5	1	0
42.0541	12.3906	0.9	0.5	0	0	1	0
42.0541	12.3906	0.9	0.45	0.9	0.9	0	1
42.0541	12.3906	0.9	0.45	0.75	0.6	0	1
42.0541	12.3906	0.9	0.45	0.5	0.7	0	1
42.0541	12.3906	0.9	0.45	0.4	0.5	1	0
42.0541	12.3906	0.9	0.45	0	0	1	0
42.0541	12.3906	0.9	0	0.9	0.9	1	0
42.0541	12.3906	0.9	0	0.75	0.6	1	0
42.0541	12.3906	0.9	0	0.5	0.7	1	0
42.0541	12.3906	0.9	0	0.4	0.5	1	0
42.0541	12.3906	0.9	0	0	0	1	0
42.0541	12.3906	0.75	0.9	0.9	0.9	0	1
42.0541	12.3906	0.75	0.9	0.75	0.6	0	1
42.0541	12.3906	0.75	0.9	0.5	0.7	0	1
42.0541	12.3906	0.75	0.9	0.4	0.5	1	0
42.0541	12.3906	0.75	0.9	0	0	1	0
42.0541	12.3906	0.75	0.75	0.9	0.9	0	1
42.0541	12.3906	0.75	0.75	0.75	0.6	0	1
42.0541	12.3906	0.75	0.75	0.5	0.7	0	1
42.0541	12.3906	0.75	0.75	0.4	0.5	1	0
42.0541	12.3906	0.75	0.75	0	0	1	0
42.0541	12.3906	0.75	0.5	0.9	0.9	0	1

42.0541	12.3906	0.75	0.5	0.75	0.6	0	1
42.0541	12.3906	0.75	0.5	0.5	0.7	0	1
42.0541	12.3906	0.75	0.5	0.4	0.5	1	0
42.0541	12.3906	0.75	0.5	0	0	1	0
42.0541	12.3906	0.75	0.45	0.9	0.9	0	1
42.0541	12.3906	0.75	0.45	0.75	0.6	0	1
42.0541	12.3906	0.75	0.45	0.5	0.7	0	1
42.0541	12.3906	0.75	0.45	0.4	0.5	1	0
42.0541	12.3906	0.75	0.45	0	0	1	0
42.0541	12.3906	0.75	0	0.9	0.9	1	0
42.0541	12.3906	0.75	0	0.75	0.6	1	0
42.0541	12.3906	0.75	0	0.5	0.7	1	0
42.0541	12.3906	0.75	0	0.4	0.5	1	0
42.0541	12.3906	0.75	0	0	0	1	0
42.0541	12.3906	0.6	0.9	0.9	0.9	0	1
42.0541	12.3906	0.6	0.9	0.75	0.6	0	1
42.0541	12.3906	0.6	0.9	0.5	0.7	0	1
42.0541	12.3906	0.6	0.9	0.4	0.5	1	1
42.0541	12.3906	0.6	0.9	0	0	1	1
42.0541	12.3906	0.6	0.75	0.9	0.9	0	1
42.0541	12.3906	0.6	0.75	0.75	0.6	0	1
42.0541	12.3906	0.6	0.75	0.5	0.7	0	1
42.0541	12.3906	0.6	0.75	0.4	0.5	1	0
42.0541	12.3906	0.6	0.75	0	0	1	0
42.0541	12.3906	0.6	0.5	0.9	0.9	0	1
42.0541	12.3906	0.6	0.5	0.75	0.6	0	1
42.0541	12.3906	0.6	0.5	0.5	0.7	0	1
42.0541	12.3906	0.6	0.5	0.4	0.5	1	0
42.0541	12.3906	0.6	0.5	0	0	1	0
42.0541	12.3906	0.6	0.45	0.9	0.9	0	1
42.0541	12.3906	0.6	0.45	0.75	0.6	0	1
42.0541	12.3906	0.6	0.45	0.5	0.7	0	1
42.0541	12.3906	0.6	0.45	0.4	0.5	1	0
42.0541	12.3906	0.6	0.45	0	0	1	0
42.0541	12.3906	0.6	0	0.9	0.9	1	0
42.0541	12.3906	0.6	0	0.75	0.6	1	0
42.0541	12.3906	0.6	0	0.5	0.7	1	0
42.0541	12.3906	0.6	0	0.4	0.5	1	0
42.0541	12.3906	0.6	0	0	0	1	0
42.0541	12.3906	0.5	0.9	0.9	0.9	0	1
42.0541	12.3906	0.5	0.9	0.75	0.6	0	1
42.0541	12.3906	0.5	0.9	0.5	0.7	0	1
42.0541	12.3906	0.5	0.9	0.4	0.5	1	0
42.0541	12.3906	0.5	0.9	0	0	1	0
42.0541	12.3906	0.5	0.75	0.9	0.9	0	1
42.0541	12.3906	0.5	0.75	0.75	0.6	0	1

42.0541	12.3906	0.5	0.75	0.5	0.7	0	1
42.0541	12.3906	0.5	0.75	0.4	0.5	1	0
42.0541	12.3906	0.5	0.75	0	0	1	0
42.0541	12.3906	0.5	0.5	0.9	0.9	0	1
42.0541	12.3906	0.5	0.5	0.75	0.6	0	1
42.0541	12.3906	0.5	0.5	0.5	0.7	0	1
42.0541	12.3906	0.5	0.5	0.4	0.5	1	0
42.0541	12.3906	0.5	0.5	0	0	1	0
42.0541	12.3906	0.5	0.45	0.9	0.9	0	1
42.0541	12.3906	0.5	0.45	0.75	0.6	0	1
42.0541	12.3906	0.5	0.45	0.5	0.7	0	1
42.0541	12.3906	0.5	0.45	0.4	0.5	1	0
42.0541	12.3906	0.5	0.45	0	0	1	0
42.0541	12.3906	0.5	0	0.9	0.9	1	0
42.0541	12.3906	0.5	0	0.75	0.6	1	0
42.0541	12.3906	0.5	0	0.5	0.7	1	0
42.0541	12.3906	0.5	0	0.4	0.5	1	0
42.0541	12.3906	0.5	0	0	0	1	0
42.0541	12.3906	0.35	0.9	0.9	0.9	0	1
42.0541	12.3906	0.35	0.9	0.75	0.6	0	1
42.0541	12.3906	0.35	0.9	0.5	0.7	0	1
42.0541	12.3906	0.35	0.9	0.4	0.5	1	0
42.0541	12.3906	0.35	0.9	0	0	1	0
42.0541	12.3906	0.35	0.75	0.9	0.9	0	1
42.0541	12.3906	0.35	0.75	0.75	0.6	0	1
42.0541	12.3906	0.35	0.75	0.5	0.7	0	1
42.0541	12.3906	0.35	0.75	0.4	0.5	1	0
42.0541	12.3906	0.35	0.75	0	0	1	0
42.0541	12.3906	0.35	0.5	0.9	0.9	0	1
42.0541	12.3906	0.35	0.5	0.75	0.6	0	1
42.0541	12.3906	0.35	0.5	0.5	0.7	0	1
42.0541	12.3906	0.35	0.5	0.4	0.5	1	0
42.0541	12.3906	0.35	0.5	0	0	1	0
42.0541	12.3906	0.35	0.45	0.9	0.9	0	1
42.0541	12.3906	0.35	0.45	0.75	0.6	0	1
42.0541	12.3906	0.35	0.45	0.5	0.7	0	1
42.0541	12.3906	0.35	0.45	0.4	0.5	1	0
42.0541	12.3906	0.35	0.45	0	0	1	0
42.0541	12.3906	0.35	0	0.9	0.9	1	0
42.0541	12.3906	0.35	0	0.75	0.6	1	0
42.0541	12.3906	0.35	0	0.5	0.7	1	0
42.0541	12.3906	0.35	0	0.4	0.5	1	0
42.0541	12.3906	0.35	0	0	0	1	0
42.0541	12.3906	0.2	0.9	0.9	0.9	0	1
42.0541	12.3906	0.2	0.9	0.75	0.6	0	1
42.0541	12.3906	0.2	0.9	0.5	0.7	0	1

42.0541	12.3906	0.2	0.9	0.4	0.5	1	0
42.0541	12.3906	0.2	0.9	0	0	1	0
42.0541	12.3906	0.2	0.75	0.9	0.9	0	1
42.0541	12.3906	0.2	0.75	0.75	0.6	0	1
42.0541	12.3906	0.2	0.75	0.5	0.7	0	1
42.0541	12.3906	0.2	0.75	0.4	0.5	1	0
42.0541	12.3906	0.2	0.75	0	0	1	0
42.0541	12.3906	0.2	0.5	0.9	0.9	0	1
42.0541	12.3906	0.2	0.5	0.75	0.6	0	1
42.0541	12.3906	0.2	0.5	0.5	0.7	0	1
42.0541	12.3906	0.2	0.5	0.4	0.5	1	0
42.0541	12.3906	0.2	0.5	0	0	1	0
42.0541	12.3906	0.2	0.45	0.9	0.9	0	1
42.0541	12.3906	0.2	0.45	0.75	0.6	0	1
42.0541	12.3906	0.2	0.45	0.5	0.7	0	1
42.0541	12.3906	0.2	0.45	0.4	0.5	1	0
42.0541	12.3906	0.2	0.45	0	0	1	0
42.0541	12.3906	0.2	0	0.9	0.9	1	0
42.0541	12.3906	0.2	0	0.75	0.6	1	0
42.0541	12.3906	0.2	0	0.5	0.7	1	0
42.0541	12.3906	0.2	0	0.4	0.5	1	0
42.0541	12.3906	0.2	0	0	0	1	0
42.0541	12.3906	0	0.9	0.9	0.9	0	1
42.0541	12.3906	0	0.9	0.75	0.6	0	1
42.0541	12.3906	0	0.9	0.5	0.7	0	1
42.0541	12.3906	0	0.9	0.4	0.5	0	1
42.0541	12.3906	0	0.9	0	0	0	1
42.0541	12.3906	0	0.75	0.9	0.9	0	1
42.0541	12.3906	0	0.75	0.75	0.6	0	1
42.0541	12.3906	0	0.75	0.5	0.7	0	1
42.0541	12.3906	0	0.75	0.4	0.5	0	1
42.0541	12.3906	0	0.75	0	0	0	1
42.0541	12.3906	0	0.5	0.9	0.9	0	1
42.0541	12.3906	0	0.5	0.75	0.6	0	1
42.0541	12.3906	0	0.5	0.5	0.7	0	1
42.0541	12.3906	0	0.5	0.4	0.5	0	1
42.0541	12.3906	0	0.5	0	0	0	1
42.0541	12.3906	0	0.45	0.9	0.9	0	1
42.0541	12.3906	0	0.45	0.75	0.6	0	1
42.0541	12.3906	0	0.45	0.5	0.7	0	1
42.0541	12.3906	0	0.45	0.4	0.5	0	1
42.0541	12.3906	0	0.45	0	0	0	1
42.0541	12.3906	0	0	0.9	0.9	1	0
42.0541	12.3906	0	0	0.75	0.6	1	0
42.0541	12.3906	0	0	0.5	0.7	1	0
42.0541	12.3906	0	0	0.4	0.5	1	0

42.0541	12.3906	0	0	0	0	1	0
42.0591	12.3873	0.9	0.9	0.9	0.9	0	1
42.0591	12.3873	0.9	0.9	0.75	0.6	0	1
42.0591	12.3873	0.9	0.9	0.5	0.7	0	1
42.0591	12.3873	0.9	0.9	0.4	0.5	1	0
42.0591	12.3873	0.9	0.9	0	0	1	0
42.0591	12.3873	0.9	0.75	0.9	0.9	0	1
42.0591	12.3873	0.9	0.75	0.75	0.6	0	1
42.0591	12.3873	0.9	0.75	0.5	0.7	0	1
42.0591	12.3873	0.9	0.75	0.4	0.5	1	0
42.0591	12.3873	0.9	0.75	0	0	1	0
42.0591	12.3873	0.9	0.5	0.9	0.9	0	1
42.0591	12.3873	0.9	0.5	0.75	0.6	0	1
42.0591	12.3873	0.9	0.5	0.5	0.7	0	1
42.0591	12.3873	0.9	0.5	0.4	0.5	1	0
42.0591	12.3873	0.9	0.5	0	0	1	0
42.0591	12.3873	0.9	0.45	0.9	0.9	0	1
42.0591	12.3873	0.9	0.45	0.75	0.6	0	1
42.0591	12.3873	0.9	0.45	0.5	0.7	0	1
42.0591	12.3873	0.9	0.45	0.4	0.5	1	0
42.0591	12.3873	0.9	0.45	0	0	1	0
42.0591	12.3873	0.9	0	0.9	0.9	1	0
42.0591	12.3873	0.9	0	0.75	0.6	1	0
42.0591	12.3873	0.9	0	0.5	0.7	1	0
42.0591	12.3873	0.9	0	0.4	0.5	1	0
42.0591	12.3873	0.9	0	0	0	1	0
42.0591	12.3873	0.75	0.9	0.9	0.9	0	1
42.0591	12.3873	0.75	0.9	0.75	0.6	0	1
42.0591	12.3873	0.75	0.9	0.5	0.7	0	1
42.0591	12.3873	0.75	0.9	0.4	0.5	1	0
42.0591	12.3873	0.75	0.9	0	0	1	0
42.0591	12.3873	0.75	0.75	0.9	0.9	0	1
42.0591	12.3873	0.75	0.75	0.75	0.6	0	1
42.0591	12.3873	0.75	0.75	0.5	0.7	0	1
42.0591	12.3873	0.75	0.75	0.4	0.5	1	0
42.0591	12.3873	0.75	0.75	0	0	1	0
42.0591	12.3873	0.75	0.5	0.9	0.9	0	1
42.0591	12.3873	0.75	0.5	0.75	0.6	0	1
42.0591	12.3873	0.75	0.5	0.5	0.7	0	1
42.0591	12.3873	0.75	0.5	0.4	0.5	1	0
42.0591	12.3873	0.75	0.5	0	0	1	0
42.0591	12.3873	0.75	0.45	0.9	0.9	0	1
42.0591	12.3873	0.75	0.45	0.75	0.6	0	1
42.0591	12.3873	0.75	0.45	0.5	0.7	0	1
42.0591	12.3873	0.75	0.45	0.4	0.5	1	0
42.0591	12.3873	0.75	0.45	0	0	1	0

42.0591	12.3873	0.75	0	0.9	0.9	1	0
42.0591	12.3873	0.75	0	0.75	0.6	1	0
42.0591	12.3873	0.75	0	0.5	0.7	1	0
42.0591	12.3873	0.75	0	0.4	0.5	1	0
42.0591	12.3873	0.75	0	0	0	1	0
42.0591	12.3873	0.6	0.9	0.9	0.9	0	1
42.0591	12.3873	0.6	0.9	0.75	0.6	0	1
42.0591	12.3873	0.6	0.9	0.5	0.7	0	1
42.0591	12.3873	0.6	0.9	0.4	0.5	1	1
42.0591	12.3873	0.6	0.9	0	0	1	1
42.0591	12.3873	0.6	0.75	0.9	0.9	0	1
42.0591	12.3873	0.6	0.75	0.75	0.6	0	1
42.0591	12.3873	0.6	0.75	0.5	0.7	0	1
42.0591	12.3873	0.6	0.75	0.4	0.5	1	0
42.0591	12.3873	0.6	0.75	0	0	1	0
42.0591	12.3873	0.6	0.5	0.9	0.9	0	1
42.0591	12.3873	0.6	0.5	0.75	0.6	0	1
42.0591	12.3873	0.6	0.5	0.5	0.7	0	1
42.0591	12.3873	0.6	0.5	0.4	0.5	1	0
42.0591	12.3873	0.6	0.5	0	0	1	0
42.0591	12.3873	0.6	0.45	0.9	0.9	0	1
42.0591	12.3873	0.6	0.45	0.75	0.6	0	1
42.0591	12.3873	0.6	0.45	0.5	0.7	0	1
42.0591	12.3873	0.6	0.45	0.4	0.5	1	0
42.0591	12.3873	0.6	0.45	0	0	1	0
42.0591	12.3873	0.6	0	0.9	0.9	1	0
42.0591	12.3873	0.6	0	0.75	0.6	1	0
42.0591	12.3873	0.6	0	0.5	0.7	1	0
42.0591	12.3873	0.6	0	0.4	0.5	1	0
42.0591	12.3873	0.6	0	0	0	1	0
42.0591	12.3873	0.5	0.9	0.9	0.9	0	1
42.0591	12.3873	0.5	0.9	0.75	0.6	0	1
42.0591	12.3873	0.5	0.9	0.5	0.7	0	1
42.0591	12.3873	0.5	0.9	0.4	0.5	1	0
42.0591	12.3873	0.5	0.9	0	0	1	0
42.0591	12.3873	0.5	0.75	0.9	0.9	0	1
42.0591	12.3873	0.5	0.75	0.75	0.6	0	1
42.0591	12.3873	0.5	0.75	0.5	0.7	0	1
42.0591	12.3873	0.5	0.75	0.4	0.5	1	0
42.0591	12.3873	0.5	0.75	0	0	1	0
42.0591	12.3873	0.5	0.5	0.9	0.9	0	1
42.0591	12.3873	0.5	0.5	0.75	0.6	0	1
42.0591	12.3873	0.5	0.5	0.5	0.7	0	1
42.0591	12.3873	0.5	0.5	0.4	0.5	1	0
42.0591	12.3873	0.5	0.5	0	0	1	0
42.0591	12.3873	0.5	0.45	0.9	0.9	0	1

42.0591	12.3873	0.5	0.45	0.75	0.6	0	1
42.0591	12.3873	0.5	0.45	0.5	0.7	0	1
42.0591	12.3873	0.5	0.45	0.4	0.5	1	0
42.0591	12.3873	0.5	0.45	0	0	1	0
42.0591	12.3873	0.5	0	0.9	0.9	1	0
42.0591	12.3873	0.5	0	0.75	0.6	1	0
42.0591	12.3873	0.5	0	0.5	0.7	1	0
42.0591	12.3873	0.5	0	0.4	0.5	1	0
42.0591	12.3873	0.5	0	0	0	1	0
42.0591	12.3873	0.35	0.9	0.9	0.9	0	1
42.0591	12.3873	0.35	0.9	0.75	0.6	0	1
42.0591	12.3873	0.35	0.9	0.5	0.7	0	1
42.0591	12.3873	0.35	0.9	0.4	0.5	1	0
42.0591	12.3873	0.35	0.9	0	0	1	0
42.0591	12.3873	0.35	0.75	0.9	0.9	0	1
42.0591	12.3873	0.35	0.75	0.75	0.6	0	1
42.0591	12.3873	0.35	0.75	0.5	0.7	0	1
42.0591	12.3873	0.35	0.75	0.4	0.5	1	0
42.0591	12.3873	0.35	0.75	0	0	1	0
42.0591	12.3873	0.35	0.5	0.9	0.9	0	1
42.0591	12.3873	0.35	0.5	0.75	0.6	0	1
42.0591	12.3873	0.35	0.5	0.5	0.7	0	1
42.0591	12.3873	0.35	0.5	0.4	0.5	1	0
42.0591	12.3873	0.35	0.5	0	0	1	0
42.0591	12.3873	0.35	0.45	0.9	0.9	0	1
42.0591	12.3873	0.35	0.45	0.75	0.6	0	1
42.0591	12.3873	0.35	0.45	0.5	0.7	0	1
42.0591	12.3873	0.35	0.45	0.4	0.5	1	0
42.0591	12.3873	0.35	0.45	0	0	1	0
42.0591	12.3873	0.35	0	0.9	0.9	1	0
42.0591	12.3873	0.35	0	0.75	0.6	1	0
42.0591	12.3873	0.35	0	0.5	0.7	1	0
42.0591	12.3873	0.35	0	0.4	0.5	1	0
42.0591	12.3873	0.35	0	0	0	1	0
42.0591	12.3873	0.2	0.9	0.9	0.9	0	1
42.0591	12.3873	0.2	0.9	0.75	0.6	0	1
42.0591	12.3873	0.2	0.9	0.5	0.7	0	1
42.0591	12.3873	0.2	0.9	0.4	0.5	1	0
42.0591	12.3873	0.2	0.9	0	0	1	0
42.0591	12.3873	0.2	0.75	0.9	0.9	0	1
42.0591	12.3873	0.2	0.75	0.75	0.6	0	1
42.0591	12.3873	0.2	0.75	0.5	0.7	0	1
42.0591	12.3873	0.2	0.75	0.4	0.5	1	0
42.0591	12.3873	0.2	0.75	0	0	1	0
42.0591	12.3873	0.2	0.5	0.9	0.9	0	1
42.0591	12.3873	0.2	0.5	0.75	0.6	0	1

42.0591	12.3873	0.2	0.5	0.5	0.7	0	1
42.0591	12.3873	0.2	0.5	0.4	0.5	1	0
42.0591	12.3873	0.2	0.5	0	0	1	0
42.0591	12.3873	0.2	0.45	0.9	0.9	0	1
42.0591	12.3873	0.2	0.45	0.75	0.6	0	1
42.0591	12.3873	0.2	0.45	0.5	0.7	0	1
42.0591	12.3873	0.2	0.45	0.4	0.5	1	0
42.0591	12.3873	0.2	0.45	0	0	1	0
42.0591	12.3873	0.2	0	0.9	0.9	1	0
42.0591	12.3873	0.2	0	0.75	0.6	1	0
42.0591	12.3873	0.2	0	0.5	0.7	1	0
42.0591	12.3873	0.2	0	0.4	0.5	1	0
42.0591	12.3873	0.2	0	0	0	1	0
42.0591	12.3873	0	0.9	0.9	0.9	0	1
42.0591	12.3873	0	0.9	0.75	0.6	0	1
42.0591	12.3873	0	0.9	0.5	0.7	0	1
42.0591	12.3873	0	0.9	0.4	0.5	0	1
42.0591	12.3873	0	0.9	0	0	0	1
42.0591	12.3873	0	0.75	0.9	0.9	0	1
42.0591	12.3873	0	0.75	0.75	0.6	0	1
42.0591	12.3873	0	0.75	0.5	0.7	0	1
42.0591	12.3873	0	0.75	0.4	0.5	0	1
42.0591	12.3873	0	0.75	0	0	0	1
42.0591	12.3873	0	0.5	0.9	0.9	0	1
42.0591	12.3873	0	0.5	0.75	0.6	0	1
42.0591	12.3873	0	0.5	0.5	0.7	0	1
42.0591	12.3873	0	0.5	0.4	0.5	0	1
42.0591	12.3873	0	0.5	0	0	0	1
42.0591	12.3873	0	0.45	0.9	0.9	0	1
42.0591	12.3873	0	0.45	0.75	0.6	0	1
42.0591	12.3873	0	0.45	0.5	0.7	0	1
42.0591	12.3873	0	0.45	0.4	0.5	0	1
42.0591	12.3873	0	0.45	0	0	0	1
42.0591	12.3873	0	0	0.9	0.9	1	0
42.0591	12.3873	0	0	0.75	0.6	1	0
42.0591	12.3873	0	0	0.5	0.7	1	0
42.0591	12.3873	0	0	0.4	0.5	1	0
42.0591	12.3873	0	0	0	0	1	0
42.0587	12.3873	0.9	0.9	0.9	0.9	0	1
42.0587	12.3873	0.9	0.9	0.75	0.6	0	1
42.0587	12.3873	0.9	0.9	0.5	0.7	0	1
42.0587	12.3873	0.9	0.9	0.4	0.5	1	0
42.0587	12.3873	0.9	0.9	0	0	1	0
42.0587	12.3873	0.9	0.75	0.9	0.9	0	1
42.0587	12.3873	0.9	0.75	0.75	0.6	0	1
42.0587	12.3873	0.9	0.75	0.5	0.7	0	1

42.0587	12.3873	0.9	0.75	0.4	0.5	1	0
42.0587	12.3873	0.9	0.75	0	0	1	0
42.0587	12.3873	0.9	0.5	0.9	0.9	0	1
42.0587	12.3873	0.9	0.5	0.75	0.6	0	1
42.0587	12.3873	0.9	0.5	0.5	0.7	0	1
42.0587	12.3873	0.9	0.5	0.4	0.5	1	0
42.0587	12.3873	0.9	0.5	0	0	1	0
42.0587	12.3873	0.9	0.45	0.9	0.9	0	1
42.0587	12.3873	0.9	0.45	0.75	0.6	0	1
42.0587	12.3873	0.9	0.45	0.5	0.7	0	1
42.0587	12.3873	0.9	0.45	0.4	0.5	1	0
42.0587	12.3873	0.9	0.45	0	0	1	0
42.0587	12.3873	0.9	0	0.9	0.9	1	0
42.0587	12.3873	0.9	0	0.75	0.6	1	0
42.0587	12.3873	0.9	0	0.5	0.7	1	0
42.0587	12.3873	0.9	0	0.4	0.5	1	0
42.0587	12.3873	0.9	0	0	0	1	0
42.0587	12.3873	0.75	0.9	0.9	0.9	0	1
42.0587	12.3873	0.75	0.9	0.75	0.6	0	1
42.0587	12.3873	0.75	0.9	0.5	0.7	0	1
42.0587	12.3873	0.75	0.9	0.4	0.5	1	0
42.0587	12.3873	0.75	0.9	0	0	1	0
42.0587	12.3873	0.75	0.75	0.9	0.9	0	1
42.0587	12.3873	0.75	0.75	0.75	0.6	0	1
42.0587	12.3873	0.75	0.75	0.5	0.7	0	1
42.0587	12.3873	0.75	0.75	0.4	0.5	1	0
42.0587	12.3873	0.75	0.75	0	0	1	0
42.0587	12.3873	0.75	0.5	0.9	0.9	0	1
42.0587	12.3873	0.75	0.5	0.75	0.6	0	1
42.0587	12.3873	0.75	0.5	0.5	0.7	0	1
42.0587	12.3873	0.75	0.5	0.4	0.5	1	0
42.0587	12.3873	0.75	0.5	0	0	1	0
42.0587	12.3873	0.75	0.45	0.9	0.9	0	1
42.0587	12.3873	0.75	0.45	0.75	0.6	0	1
42.0587	12.3873	0.75	0.45	0.5	0.7	0	1
42.0587	12.3873	0.75	0.45	0.4	0.5	1	0
42.0587	12.3873	0.75	0.45	0	0	1	0
42.0587	12.3873	0.75	0	0.9	0.9	1	0
42.0587	12.3873	0.75	0	0.75	0.6	1	0
42.0587	12.3873	0.75	0	0.5	0.7	1	0
42.0587	12.3873	0.75	0	0.4	0.5	1	0
42.0587	12.3873	0.75	0	0	0	1	0
42.0587	12.3873	0.6	0.9	0.9	0.9	0	1
42.0587	12.3873	0.6	0.9	0.75	0.6	0	1
42.0587	12.3873	0.6	0.9	0.5	0.7	0	1
42.0587	12.3873	0.6	0.9	0.4	0.5	1	1

42.0587	12.3873	0.6	0.9	0	0	1	1
42.0587	12.3873	0.6	0.75	0.9	0.9	0	1
42.0587	12.3873	0.6	0.75	0.75	0.6	0	1
42.0587	12.3873	0.6	0.75	0.5	0.7	0	1
42.0587	12.3873	0.6	0.75	0.4	0.5	1	0
42.0587	12.3873	0.6	0.75	0	0	1	0
42.0587	12.3873	0.6	0.5	0.9	0.9	0	1
42.0587	12.3873	0.6	0.5	0.75	0.6	0	1
42.0587	12.3873	0.6	0.5	0.5	0.7	0	1
42.0587	12.3873	0.6	0.5	0.4	0.5	1	0
42.0587	12.3873	0.6	0.5	0	0	1	0
42.0587	12.3873	0.6	0.45	0.9	0.9	0	1
42.0587	12.3873	0.6	0.45	0.75	0.6	0	1
42.0587	12.3873	0.6	0.45	0.5	0.7	0	1
42.0587	12.3873	0.6	0.45	0.4	0.5	1	0
42.0587	12.3873	0.6	0.45	0	0	1	0
42.0587	12.3873	0.6	0	0.9	0.9	1	0
42.0587	12.3873	0.6	0	0.75	0.6	1	0
42.0587	12.3873	0.6	0	0.5	0.7	1	0
42.0587	12.3873	0.6	0	0.4	0.5	1	0
42.0587	12.3873	0.6	0	0	0	1	0
42.0587	12.3873	0.5	0.9	0.9	0.9	0	1
42.0587	12.3873	0.5	0.9	0.75	0.6	0	1
42.0587	12.3873	0.5	0.9	0.5	0.7	0	1
42.0587	12.3873	0.5	0.9	0.4	0.5	1	0
42.0587	12.3873	0.5	0.9	0	0	1	0
42.0587	12.3873	0.5	0.75	0.9	0.9	0	1
42.0587	12.3873	0.5	0.75	0.75	0.6	0	1
42.0587	12.3873	0.5	0.75	0.5	0.7	0	1
42.0587	12.3873	0.5	0.75	0.4	0.5	1	0
42.0587	12.3873	0.5	0.75	0	0	1	0
42.0587	12.3873	0.5	0.5	0.9	0.9	0	1
42.0587	12.3873	0.5	0.5	0.75	0.6	0	1
42.0587	12.3873	0.5	0.5	0.5	0.7	0	1
42.0587	12.3873	0.5	0.5	0.4	0.5	1	0
42.0587	12.3873	0.5	0.5	0	0	1	0
42.0587	12.3873	0.5	0.45	0.9	0.9	0	1
42.0587	12.3873	0.5	0.45	0.75	0.6	0	1
42.0587	12.3873	0.5	0.45	0.5	0.7	0	1
42.0587	12.3873	0.5	0.45	0.4	0.5	1	0
42.0587	12.3873	0.5	0.45	0	0	1	0
42.0587	12.3873	0.5	0	0.9	0.9	1	0
42.0587	12.3873	0.5	0	0.75	0.6	1	0
42.0587	12.3873	0.5	0	0.5	0.7	1	0
42.0587	12.3873	0.5	0	0.4	0.5	1	0
42.0587	12.3873	0.5	0	0	0	1	0

42.0587	12.3873	0.35	0.9	0.9	0.9	0	1
42.0587	12.3873	0.35	0.9	0.75	0.6	0	1
42.0587	12.3873	0.35	0.9	0.5	0.7	0	1
42.0587	12.3873	0.35	0.9	0.4	0.5	1	0
42.0587	12.3873	0.35	0.9	0	0	1	0
42.0587	12.3873	0.35	0.75	0.9	0.9	0	1
42.0587	12.3873	0.35	0.75	0.75	0.6	0	1
42.0587	12.3873	0.35	0.75	0.5	0.7	0	1
42.0587	12.3873	0.35	0.75	0.4	0.5	1	0
42.0587	12.3873	0.35	0.75	0	0	1	0
42.0587	12.3873	0.35	0.5	0.9	0.9	0	1
42.0587	12.3873	0.35	0.5	0.75	0.6	0	1
42.0587	12.3873	0.35	0.5	0.5	0.7	0	1
42.0587	12.3873	0.35	0.5	0.4	0.5	1	0
42.0587	12.3873	0.35	0.5	0	0	1	0
42.0587	12.3873	0.35	0.45	0.9	0.9	0	1
42.0587	12.3873	0.35	0.45	0.75	0.6	0	1
42.0587	12.3873	0.35	0.45	0.5	0.7	0	1
42.0587	12.3873	0.35	0.45	0.4	0.5	1	0
42.0587	12.3873	0.35	0.45	0	0	1	0
42.0587	12.3873	0.35	0	0.9	0.9	1	0
42.0587	12.3873	0.35	0	0.75	0.6	1	0
42.0587	12.3873	0.35	0	0.5	0.7	1	0
42.0587	12.3873	0.35	0	0.4	0.5	1	0
42.0587	12.3873	0.35	0	0	0	1	0
42.0587	12.3873	0.2	0.9	0.9	0.9	0	1
42.0587	12.3873	0.2	0.9	0.75	0.6	0	1
42.0587	12.3873	0.2	0.9	0.5	0.7	0	1
42.0587	12.3873	0.2	0.9	0.4	0.5	1	0
42.0587	12.3873	0.2	0.9	0	0	1	0
42.0587	12.3873	0.2	0.75	0.9	0.9	0	1
42.0587	12.3873	0.2	0.75	0.75	0.6	0	1
42.0587	12.3873	0.2	0.75	0.5	0.7	0	1
42.0587	12.3873	0.2	0.75	0.4	0.5	1	0
42.0587	12.3873	0.2	0.75	0	0	1	0
42.0587	12.3873	0.2	0.5	0.9	0.9	0	1
42.0587	12.3873	0.2	0.5	0.75	0.6	0	1
42.0587	12.3873	0.2	0.5	0.5	0.7	0	1
42.0587	12.3873	0.2	0.5	0.4	0.5	1	0
42.0587	12.3873	0.2	0.5	0	0	1	0
42.0587	12.3873	0.2	0.45	0.9	0.9	0	1
42.0587	12.3873	0.2	0.45	0.75	0.6	0	1
42.0587	12.3873	0.2	0.45	0.5	0.7	0	1
42.0587	12.3873	0.2	0.45	0.4	0.5	1	0
42.0587	12.3873	0.2	0.45	0	0	1	0
42.0587	12.3873	0.2	0	0.9	0.9	1	0

42.0587	12.3873	0.2	0	0.75	0.6	1	0
42.0587	12.3873	0.2	0	0.5	0.7	1	0
42.0587	12.3873	0.2	0	0.4	0.5	1	0
42.0587	12.3873	0.2	0	0	0	1	0
42.0587	12.3873	0	0.9	0.9	0.9	0	1
42.0587	12.3873	0	0.9	0.75	0.6	0	1
42.0587	12.3873	0	0.9	0.5	0.7	0	1
42.0587	12.3873	0	0.9	0.4	0.5	0	1
42.0587	12.3873	0	0.9	0	0	0	1
42.0587	12.3873	0	0.75	0.9	0.9	0	1
42.0587	12.3873	0	0.75	0.75	0.6	0	1
42.0587	12.3873	0	0.75	0.5	0.7	0	1
42.0587	12.3873	0	0.75	0.4	0.5	0	1
42.0587	12.3873	0	0.75	0	0	0	1
42.0587	12.3873	0	0.5	0.9	0.9	0	1
42.0587	12.3873	0	0.5	0.75	0.6	0	1
42.0587	12.3873	0	0.5	0.5	0.7	0	1
42.0587	12.3873	0	0.5	0.4	0.5	0	1
42.0587	12.3873	0	0.5	0	0	0	1
42.0587	12.3873	0	0.45	0.9	0.9	0	1
42.0587	12.3873	0	0.45	0.75	0.6	0	1
42.0587	12.3873	0	0.45	0.5	0.7	0	1
42.0587	12.3873	0	0.45	0.4	0.5	0	1
42.0587	12.3873	0	0.45	0	0	0	1
42.0587	12.3873	0	0	0.9	0.9	1	0
42.0587	12.3873	0	0	0.75	0.6	1	0
42.0587	12.3873	0	0	0.5	0.7	1	0
42.0587	12.3873	0	0	0.4	0.5	1	0
42.0587	12.3873	0	0	0	0	1	0
42.0641	12.3839	0.9	0.9	0.9	0.9	0	1
42.0641	12.3839	0.9	0.75	0.75	0.75	0	1
42.0641	12.3839	0.9	0.5	0.5	0.5	0	1
42.0641	12.3839	0.9	0.45	0.45	0.45	0	1
42.0641	12.3839	0.9	0	0	0	1	0
42.0641	12.3839	0.75	0.9	0.9	0.9	0	1
42.0641	12.3839	0.75	0.75	0.75	0.75	0	1
42.0641	12.3839	0.75	0.5	0.5	0.5	0	1
42.0641	12.3839	0.75	0.45	0.45	0.45	0	1
42.0641	12.3839	0.75	0	0	0	1	0
42.0641	12.3839	0.6	0.9	0.9	0.9	0	1
42.0641	12.3839	0.6	0.75	0.75	0.75	0	1
42.0641	12.3839	0.6	0.5	0.5	0.5	0	1
42.0641	12.3839	0.6	0.3	0.3	0.3	0	1
42.0641	12.3839	0.6	0	0	0	1	0
42.0641	12.3839	0.5	0.9	0.9	0.9	0	1
42.0641	12.3839	0.5	0.75	0.75	0.75	0	1

42.0641	12.3839	0.5	0.5	0.5	0.5	0	1
42.0641	12.3839	0.5	0.3	0.3	0.3	0	1
42.0641	12.3839	0.5	0	0	0	1	0
42.0641	12.3839	0.35	0.9	0.9	0.9	0	1
42.0641	12.3839	0.35	0.75	0.75	0.75	0	1
42.0641	12.3839	0.35	0.5	0.5	0.5	0	1
42.0641	12.3839	0.35	0.3	0.3	0.3	0	1
42.0641	12.3839	0.35	0	0	0	1	0
42.0641	12.3839	0.2	0.9	0.9	0.9	0	1
42.0641	12.3839	0.2	0.75	0.75	0.75	0	1
42.0641	12.3839	0.2	0.5	0.5	0.5	0	1
42.0641	12.3839	0.2	0.3	0.3	0.3	0	1
42.0641	12.3839	0.2	0	0	0	1	0
42.0641	12.3839	0	0.9	0.9	0.9	0	1
42.0641	12.3839	0	0.75	0.75	0.75	0	1
42.0641	12.3839	0	0.5	0.5	0.5	0	1
42.0641	12.3839	0	0.3	0.3	0.3	0	1
42.0641	12.3839	0	0	0	0	0	1

Table C- 1: Extract of Dataset 1 using in Training, Validation and Testing of the PCNN system

Inputs						Targetted Output	
Latitude	Longitude	SAT RSS	WLAN RSS	QoS	BW	SAT-Seg	WLAN-Seg
41.89	12.5	0.9	0	0.2	0.4	1	0
41.89	12.5	0.6	0.4	0.6	0.4	1	0
41.895	12.4967	0.9	0.13	0.7	0.7	1	0
41.8999	12.4934	0.88	0.26	0.5	0.7	1	0
41.9049	12.4901	0.89	0.39	0.9	0.7	1	0
41.9099	12.4867	0.9	0.52	0.5	0.8	1	0
41.9149	12.4834	0.9	0.65	0.9	0.6	0	1
41.9149	12.4834	0.89	0.67	0.4	0.5	1	0
41.9157	12.4834	0.88	0.68	0.75	0.5	0	1
41.9157	12.4834	0.9	0.73	0.7	0.6	0	1
41.9157	12.4834	0.9	0.77	0.4	0.5	1	0
41.9157	12.4834	0.9	0.77	0.7	0.7	0	1
41.9198	12.4801	0	0.8	0.7	0.5	0	1
41.9198	12.4801	0	0.8	0.8	0.7	0	1
41.9198	12.4801	0	0.8	0.9	0.6	0	1
41.9198	12.4801	0	0.8	0.4	0.9	0	1
41.9198	12.4801	0	0.8	0.9	0.9	0	1
41.9198	12.4801	0	0.8	0.6	0.6	0	1
41.9198	12.4801	0	0.8	0.2	0.4	0	1
41.9198	12.4801	0	0.8	0.6	0.8	0	1

41.9198	12.4801	0	0.8	0.9	0.2	0	1
41.9198	12.4801	0	0.8	0.3	0.3	0	1
41.965	12.4605	0.9	0.75	0.3	0.4	0	1
41.965	12.4605	0.9	0.75	0.7	0.9	1	0
41.9696	12.4469	0.9	0.65	0.6	0.7	1	0
41.97	12.4436	0.9	0.6	0.8	0.6	1	0
41.97	12.4436	0.9	0.58	0.8	0.8	1	0
41.9746	12.4436	0.9	0.52	0.75	0.5	1	0
41.9795	12.4403	0.9	0.39	0.5	0.6	1	0
41.9845	12.437	0.9	0.26	0.8	0.7	1	0
41.9895	12.4337	0.9	0.13	0.5	0.7	1	0
41.9944	12.4304	0.9	0	0.9	0.8	1	0
41.9994	12.4271	0.9	0	0.8	0.7	1	0
42.0044	12.4237	0.9	0	0.5	0.7	1	0
42.0094	12.4204	0.88	0	0.9	0.9	1	0
42.0143	12.4171	0.9	0	0.9	0.5	1	0
42.0193	12.4138	0.87	0	0.7	0.7	1	0
42.0293	12.4072	0.9	0	0.9	0.5	1	0
42.0342	12.4038	0.9	0	0.8	0.6	1	0
42.0392	12.4005	0.9	0.13	0.8	0.8	1	0
42.0442	12.3972	0.9	0.26	0.75	0.8	1	0
42.0492	12.3939	0.9	0.39	0.5	0.7	1	0
42.0541	12.3906	0.9	0.52	0.4	0.3	1	0
42.0591	12.3873	0.88	0.58	0.7	0.5	0	1
42.0591	12.3873	0.88	0.58	0.4	0.3	1	0
42.0591	12.3873	0.9	0.65	0.5	0.8	0	1
42.0587	12.3873	0.9	0.75	0.6	0.7	0	1
42.0641	12.3839	0	0.8	0.7	0.5	0	1
42.0641	12.3839	0	0.8	0.8	0.7	0	1
42.0641	12.3839	0	0.8	0.9	0.6	0	1
42.0641	12.3839	0	0.8	0.4	0.9	0	1
42.0641	12.3839	0	0.8	0.9	0.9	0	1
42.0641	12.3839	0	0.8	0.6	0.6	0	1
42.0641	12.3839	0	0.8	0.2	0.4	0	1
42.0641	12.3839	0	0.8	0.6	0.8	0	1
42.0641	12.3839	0	0.8	0.9	0.2	0	1
42.0641	12.3839	0	0.8	0.3	0.3	0	1
42.1138	12.3508	0.9	0.65	0.4	0.7	0	1
42.1138	12.3508	0.9	0.65	0.7	0.6	1	0
42.1141	12.3508	0.87	0.6	0.7	0.9	1	0
42.1141	12.3508	0.9	0.56	0.6	0.7	1	0
42.1188	12.3475	0.9	0.52	0.8	0.6	1	0
42.1188	12.3475	0.88	0.45	0.8	0.8	1	0
42.1238	12.3442	0.9	0.39	0.75	0.5	1	0
42.1287	12.3408	0.9	0.26	0.5	0.6	1	0
42.1337	12.3375	0.9	0.13	0.8	0.7	1	0

42.1387	12.3342	0.9	0	0.5	0.7	1	0
42.1437	12.3309	0.9	0	0.9	0.8	1	0
42.1486	12.3276	0.9	0	0.8	0.7	1	0
42.1536	12.3243	0.9	0	0.5	0.7	1	0
42.1586	12.3209	0.89	0	0.9	0.9	1	0
42.1636	12.3176	0.87	0	0.9	0.5	1	0
42.1685	12.3143	0.87	0	0.7	0.7	1	0
42.1735	12.311	0.88	0	0.4	0.5	1	0
42.1785	12.3077	0.9	0	0.9	0.5	1	0
42.1834	12.3044	0.9	0	0.8	0.6	1	0
42.1884	12.3011	0.9	0	0.8	0.8	1	0
42.1934	12.2977	0.9	0	0.75	0.8	1	0
42.1984	12.2944	0.9	0	0.5	0.7	1	0
42.2033	12.2911	0.9	0	0.4	0.3	1	0
42.2083	12.2878	0.9	0	0.5	0.7	1	0
42.2133	12.2845	0.9	0	0.9	0.8	1	0
42.2183	12.2812	0.9	0	0.8	0.7	1	0
42.2232	12.2778	0.9	0	0.5	0.7	1	0
42.2282	12.2745	0.9	0	0.9	0.9	1	0
42.2332	12.2712	0.9	0	0.9	0.5	1	0
42.2382	12.2679	0.9	0	0.7	0.7	1	0
42.2431	12.2646	0.9	0	0.4	0.5	1	0
42.2481	12.2613	0.9	0	0.9	0.5	1	0
42.2531	12.2579	0.9	0	0.8	0.6	1	0
42.2581	12.2546	0.9	0	0.8	0.8	1	0
42.263	12.2513	0.9	0	0.75	0.8	1	0
42.268	12.248	0.9	0	0.5	0.7	1	0
42.273	12.2447	0.9	0	0.4	0.3	1	0
42.2779	12.2414	0.9	0	0.5	0.7	1	0
42.2829	12.2381	0.9	0	0.9	0.8	1	0
42.2929	12.2314	0.9	0	0.5	0.7	1	0
42.2978	12.2281	0.9	0	0.9	0.9	1	0
42.3028	12.2248	0.9	0	0.9	0.5	1	0
42.3078	12.2215	0.89	0	0.7	0.7	1	0
42.3128	12.2182	0.9	0	0.4	0.5	1	0
42.3177	12.2148	0.9	0	0.9	0.5	1	0
42.3227	12.2115	0.9	0	0.8	0.6	1	0
42.3277	12.2082	0.9	0	0.8	0.8	1	0
42.3327	12.2049	0.9	0	0.75	0.8	1	0
42.3376	12.2016	0.9	0	0.5	0.7	1	0
42.3426	12.1983	0.9	0	0.4	0.3	1	0
42.3476	12.1949	0.9	0	0.5	0.7	1	0
42.3526	12.1916	0.9	0	0.9	0.8	1	0
42.3575	12.1883	0.9	0	0.8	0.7	1	0
42.3625	12.185	0.9	0	0.5	0.7	1	0
42.3675	12.1817	0.9	0	0.9	0.9	1	0

42.3724	12.1784	0.9	0	0.9	0.5	1	0
42.3774	12.1751	0.9	0	0.7	0.7	1	0
42.3824	12.1717	0.9	0	0.4	0.5	1	0
42.3874	12.1684	0.9	0	0.9	0.5	1	0
42.3923	12.1651	0.9	0	0.8	0.6	1	0
42.3973	12.1618	0.9	0	0.8	0.8	1	0
42.4023	12.1585	0.9	0	0.75	0.8	1	0
42.4073	12.1552	0.9	0	0.5	0.7	1	0
42.4122	12.1518	0.9	0	0.4	0.3	1	0
42.4172	12.1485	0.9	0	0.5	0.7	1	0
42.4222	12.1452	0.9	0	0.9	0.8	1	0
42.4321	12.1386	0.9	0	0.5	0.7	1	0
42.4371	12.1353	0.9	0	0.9	0.9	1	0
42.4421	12.1319	0.9	0	0.9	0.5	1	0
42.4471	12.1286	0.9	0	0.7	0.7	1	0
42.452	12.1253	0.9	0	0.4	0.5	1	0
42.457	12.122	0.9	0	0.9	0.5	1	0
42.462	12.1187	0.9	0	0.8	0.6	1	0
42.4669	12.1154	0.9	0	0.8	0.8	1	0
42.4719	12.1121	0.9	0	0.75	0.8	1	0
42.4769	12.1087	0.9	0	0.5	0.7	1	0
42.4819	12.1054	0.9	0	0.4	0.3	1	0
42.4868	12.1021	0.88	0	0.4	0.3	1	0
42.4918	12.0988	0.89	0	0.5	0.7	1	0
42.4968	12.0955	0.9	0	0.9	0.8	1	0
42.5018	12.0922	0.9	0	0.8	0.7	1	0
42.5067	12.0888	0.9	0	0.5	0.7	1	0
42.5117	12.0855	0.9	0	0.9	0.9	1	0
42.5167	12.0822	0.9	0	0.9	0.5	1	0
42.5217	12.0789	0.9	0	0.7	0.7	1	0
42.5266	12.0756	0.9	0	0.9	0.5	1	0
42.5316	12.0723	0.9	0	0.8	0.6	1	0
42.5366	12.0689	0.9	0.13	0.5	0.6	1	0
42.5416	12.0656	0.9	0.26	0.5	0.7	1	0
42.5465	12.0623	0.88	0.39	0.5	0.4	1	0
42.5515	12.059	0.75	0.52	0.7	0.5	0	1
42.5515	12.059	0.5	0.4	0.3	0.4	1	0
42.5565	12.0557	0.9	0.65	0.6	0.7	0	1
42.5614	12.0524	0	0.8	0.7	0.5	0	1
42.5614	12.0524	0	0.8	0.8	0.7	0	1
42.5614	12.0524	0	0.8	0.9	0.6	0	1
42.5614	12.0524	0	0.8	0.4	0.9	0	1
42.5614	12.0524	0	0.8	0.9	0.9	0	1
42.5614	12.0524	0	0.8	0.6	0.6	0	1
42.5614	12.0524	0	0.8	0.2	0.4	0	1
42.5614	12.0524	0	0.8	0.6	0.8	0	1

42.5614	12.0524	0	0.8	0.9	0.2	0	1
42.5614	12.0524	0	0.8	0.3	0.3	0	1
42.5614	12.0524	0	0.8	0.7	0.8	0	1
42.5614	12.0524	0	0.8	0.75	0.7	0	1
42.5614	12.0524	0	0.8	0.4	0.7	0	1
42.5614	12.0524	0	0.8	0.5	0.3	0	1
42.5614	12.0524	0	0.8	0.9	0.7	0	1
42.5614	12.0524	0	0.8	0.8	0.7	0	1
42.641	11.9993	0.9	0.65	0.3	0.4	1	0
42.641	11.9993	0.9	0.65	0.75	0.6	1	0
42.646	11.996	0.9	0.52	0.55	0.75	1	0
42.651	11.9927	0.9	0.39	0.8	0.6	1	0
42.6559	11.9894	0.9	0.26	0.9	0.8	1	0
42.6609	11.9861	0.9	0.13	0.8	0.9	1	0
42.6659	11.9827	0.9	0	0.75	0.8	1	0
42.6709	11.9794	0.9	0	0.5	0.7	1	0
42.6758	11.9761	0.9	0	0.4	0.3	1	0
42.6808	11.9728	0.9	0	0.5	0.7	1	0
42.6858	11.9695	0.9	0	0.9	0.8	1	0
42.6908	11.9662	0.9	0	0.8	0.7	1	0
42.6957	11.9628	0.9	0	0.5	0.7	1	0
42.7007	11.9595	0.9	0	0.9	0.9	1	0
42.7057	11.9562	0.9	0	0.9	0.5	1	0
42.7107	11.9529	0.9	0	0.7	0.7	1	0
42.7156	11.9496	0.9	0	0.4	0.5	1	0
42.7206	11.9463	0.9	0	0.9	0.5	1	0
42.7256	11.9429	0.9	0	0.8	0.6	1	0
42.7405	11.933	0.9	0	0.5	0.7	1	0
42.7455	11.9297	0.9	0	0.5	0.7	1	0
42.7504	11.9264	0.9	0	0.9	0.8	1	0
42.7554	11.9231	0.9	0	0.8	0.7	1	0
42.7604	11.9197	0.9	0	0.5	0.7	1	0
42.7654	11.9164	0.9	0	0.9	0.9	1	0
42.7703	11.9131	0.9	0	0.9	0.5	1	0
42.7753	11.9098	0.9	0	0.7	0.7	1	0
42.7902	11.8998	0.9	0	0.75	0.8	1	0
42.7952	11.8965	0.9	0	0.4	0.3	1	0
42.8002	11.8932	0.9	0	0.5	0.7	1	0
42.8052	11.8899	0.9	0	0.9	0.8	1	0
42.8101	11.8866	0.9	0	0.8	0.7	1	0
42.8151	11.8833	0.9	0	0.5	0.7	1	0
42.8201	11.8799	0.9	0	0.9	0.9	1	0
42.8251	11.8766	0.9	0	0.9	0.5	1	0
42.83	11.8733	0.9	0	0.7	0.7	1	0
42.835	11.87	0.9	0	0.4	0.5	1	0
42.84	11.8667	0.9	0	0.9	0.5	1	0

42.8449	11.8634	0.9	0	0.75	0.8	1	0
42.8499	11.8601	0.89	0	0.5	0.7	1	0
42.8549	11.8567	0.9	0	0.4	0.3	1	0
42.8599	11.8534	0.9	0	0.4	0.3	1	0
42.8648	11.8501	0.88	0	0.5	0.7	1	0
42.8698	11.8468	0.9	0	0.9	0.8	1	0
42.8798	11.8402	0.9	0	0.5	0.7	1	0
42.8847	11.8368	0.9	0	0.9	0.9	1	0
42.8897	11.8335	0.9	0	0.9	0.5	1	0
42.8947	11.8302	0.9	0	0.5	0.7	1	0
42.8997	11.8269	0.9	0	0.9	0.9	1	0
42.9046	11.8236	0.9	0	0.9	0.5	1	0
42.9096	11.8203	0.9	0	0.7	0.7	1	0
42.9146	11.8169	0.9	0	0.4	0.5	1	0
42.9196	11.8136	0.9	0	0.9	0.5	1	0
42.9245	11.8103	0.9	0	0.8	0.6	1	0
42.9295	11.807	0.9	0	0.8	0.8	1	0
42.9345	11.8037	0.9	0	0.75	0.8	1	0
42.9394	11.8004	0.9	0	0.5	0.7	1	0
42.9444	11.7971	0.9	0	0.4	0.3	1	0
42.9494	11.7937	0.9	0	0.5	0.7	1	0
42.9544	11.7904	0.9	0	0.9	0.8	1	0
42.9593	11.7871	0.9	0	0.8	0.7	1	0
42.9643	11.7838	0.9	0	0.5	0.7	1	0
42.9693	11.7805	0.9	0	0.9	0.9	1	0
42.9743	11.7772	0.9	0	0.9	0.5	1	0
42.9792	11.7738	0.9	0	0.7	0.7	1	0
42.9842	11.7705	0.9	0	0.4	0.5	1	0
42.9991	11.7606	0.9	0	0.5	0.7	1	0
43.0041	11.7573	0.9	0	0.9	0.9	1	0
43.0091	11.7539	0.9	0	0.9	0.5	1	0
43.019	11.7473	0.9	0	0.4	0.5	1	0
43.024	11.744	0.9	0	0.9	0.5	1	0
43.029	11.7407	0.9	0	0.8	0.6	1	0
43.0339	11.7374	0.9	0	0.8	0.8	1	0
43.0389	11.7341	0.9	0	0.75	0.8	1	0
43.0439	11.7307	0.9	0	0.5	0.7	1	0
43.0489	11.7274	0.9	0	0.4	0.3	1	0
43.0538	11.7241	0.9	0	0.9	0.5	1	0
43.0588	11.7208	0.9	0.13	0.9	0.9	1	0
43.0638	11.7175	0.9	0.26	0.8	0.6	1	0
43.0688	11.7142	0.9	0.39	0.4	0.5	1	0
43.0737	11.7108	0.9	0.52	0.3	0.2	1	0
43.0757	11.7092	0.9	0.6	0.4	0.3	1	0
43.0757	11.7092	0.9	0.6	0.9	0.7	0	1
43.0787	11.7075	0.9	0.65	0.85	0.5	0	1

43.0837	11.7042	0	0.8	0.7	0.5	0	1
43.0837	11.7042	0	0.8	0.8	0.7	0	1
43.0837	11.7042	0	0.8	0.9	0.6	0	1
43.0837	11.7042	0	0.8	0.4	0.9	0	1
43.0837	11.7042	0	0.8	0.9	0.9	0	1
43.0837	11.7042	0	0.8	0.6	0.6	0	1
43.0837	11.7042	0	0.8	0.2	0.4	0	1
43.0837	11.7042	0	0.8	0.6	0.8	0	1
43.0837	11.7042	0	0.8	0.9	0.2	0	1
43.0837	11.7042	0	0.8	0.3	0.3	0	1
43.0837	11.7042	0	0.8	0.7	0.8	0	1
43.0837	11.7042	0	0.8	0.75	0.7	0	1
43.0837	11.7042	0	0.8	0.4	0.7	0	1
43.0837	11.7042	0	0.8	0.5	0.3	0	1
43.0837	11.7042	0	0.8	0.9	0.7	0	1
43.0837	11.7042	0	0.8	0.8	0.7	0	1
43.1633	11.6512	0.9	0.65	0.4	0.4	0	1
43.1633	11.6512	0.9	0.65	0.75	0.8	1	0
43.1682	11.6478	0.9	0.52	0.9	0.8	1	0
43.1732	11.6445	0.9	0.39	0.75	0.5	1	0
43.1782	11.6412	0.9	0.26	0.75	0.75	1	0
43.1832	11.6379	0.9	0.13	0.8	0.4	1	0
43.1881	11.6346	0.9	0	0.5	0.7	1	0
43.1931	11.6313	0.9	0	0.9	0.8	1	0
43.1981	11.6279	0.9	0	0.8	0.7	1	0
43.2031	11.6246	0.9	0	0.5	0.7	1	0
43.208	11.6213	0.9	0	0.9	0.9	1	0
43.213	11.618	0.9	0	0.9	0.5	1	0
43.218	11.6147	0.9	0	0.7	0.7	1	0
43.2229	11.6114	0.9	0	0.4	0.5	1	0
43.2279	11.6081	0.9	0	0.4	0.3	1	0
43.2329	11.6047	0.9	0	0.5	0.7	1	0
43.2379	11.6014	0.9	0	0.9	0.8	1	0
43.2428	11.5981	0.9	0	0.8	0.7	1	0
43.2478	11.5948	0.9	0	0.5	0.7	1	0
43.2528	11.5915	0.9	0	0.9	0.9	1	0
43.2578	11.5882	0.9	0	0.9	0.5	1	0

Table C- 2: Extract of Dataset 2 using in evaluating of the trained PCNN system

APPENDIX D – LIST OF PUBLICATIONS

Journals

- F.L.C. Ong, X. Liang, P.M.L. Chan, G. Koltsidas, F.N. Pavlidou, N. Celandroni, E. Ferro, A. Gotta, H. Cruickshank, S. Iyengar, G. Fairhurst, V. Mancuso , “ Fusion of Digital Television, Broadband Internet and Mobile Communications - Part I: Enabling Technologies”, *International Journal of Satellite Communications and Networking (IJSCN)*, **25**(4), June 2007; 363-407.
- X. Liang, F.L.C. Ong, P. Pillai, P.M.L. Chan, V. Mancuso, G. Koltsidas, F.N. Pavlidou, L. Cavifkione, N. Celandroni, E. Ferro, A. Gotta, H. Cruickshank, S. Iyengar, G. Fairhurst, “Fusion of Digital Television, Broadband Internet and Mobile Communications, Part II: Future Service Scenarios”, *International Journal of Satellite Communications and Networking (IJSCN)*, **25**(4), June 2007; 409-440.

Conference

- F.L.C. Ong and P.M.L. Chan, “Fourth Generation (4G) Mobile Systems: The Development towards Heterogeneous Networking”, *Proceedings of the International Conference on Advanced Technologies in Telecommunications and Control Engineering (ATTCE 2006)*, INTI College, Kuala Lumpur, Malaysia, 28-29 August 2006.
- X. Liang, F.L.C. Ong, P.M.L. Chan, R.E. Sheriff, “Security Procedures for Broadband Communications via Satellite and W-LAN Networks to Trains”, *Proceedings of First International Symposium*

on Broadband Communications (ISBC'04), Harrogate, Leeds, 12-15 Dec 2004.

- X. Liang, F.L.C. Ong, P.M.L. Chan, R.E. Sheriff, P. Conforto, "Mobile Internet access for high-speed trains via heterogeneous networks", *Proceedings of 14th IEEE 2003 International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2003)*, Beijing, China, 7-10 September 2003; 177-181.

Poster Presentation

- F.L.C. Ong, X. Liang, P.M.L. Chan, R.E. Sheriff, "Mobile Internet Access on High-Speed Trains", *Poster Presentation at Science, Engineering and Technology (SET) for Britain*, House of Commons, London, 15 March 2004.

Other Contributions

- F.L.C. Ong, X. Liang, V.W. Chook, P.M.L. Chan, Y.F. Hu, R.E. Sheriff, "Satellite Research and Development Issues for Fourth-Generation and Ad Hoc Networks", *Contributed to ASMS-TF Report – Thematic Priority: 4G and Ad Hoc Networks*, September 2004.

Plus contribution to technical reports for various research projects – EU funded SatNEx and IST-FIFTH.